OPTIMIZING SITE LAYOUT AND MATERIAL LOGISTICS PLANNING DURING THE CONSTRUCTION OF CRITICAL INFRASTRUCTURE PROJECTS

BY

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DISSERTATION

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ABSTRACT

Optimizing Site Layout and Material Logistics Planning During the Construction of Critical Infrastructure Projects

Planning the site layout of construction projects is a crucial task that has a significant impact on construction cost, productivity, and safety. It involves the positioning and dynamic relocation of temporary facilities that are needed to support various construction activities on site such as offices, storage areas, workshops, and parking areas. Due to the complexity of the site layout planning problem, construction managers often perform this task using previous experience, ad-hoc rules, and first-come-first-serve approach which leads to ambiguity and even to inefficiency. Accordingly, a number of site layout planning models have been developed over the past three decades to support this important planning task.

Despite the contributions of existing site layout planning models, they have a number of limitations that require additional research in five main areas in order to: (1) ensure global optimization of dynamic site layout planning; (2) integrate material procurement and site layout planning in a construction logistics planning model; (3) enhance the utilization of interior building spaces for material storage areas on congested construction sites; (4) enable automated retrieval and integration of all necessary data of construction logistics and site layout planning from available design and planning documents; and (5) consider security needs and constraints during the construction of critical infrastructure projects.

Accordingly, the main objectives of this study are to: (1) formulate novel models of dynamic site layout planning (DSLP) that are capable of generating global optimal solutions of DSLP

problems by considering the effects of first stage layout decisions on the layouts of subsequent stages; (2) develop an innovative optimization model for construction logistics planning (CLP) that is capable of integrating and optimizing the critical planning decisions of material procurement and material storage on construction sites; (3) formulate a new multi-objective optimization model for Congested Construction Logistics Planning that is capable of modeling and utilizing interior and exterior spaces in order to generate optimal logistics plans for congested construction sites; (4) develop a multi-objective automated system for construction logistics optimization that enables seamless retrieval and integration of project spatial, temporal, and logistics data as well as generating and reporting optimal plans of material procurement and site layouts; and (5) formulate a multi-objective optimization framework for planning construction site layouts and site security systems of critical infrastructure projects.

First, two novel optimization models are developed that are capable of generating global optimal solutions of dynamic site layout planning in order to minimize resources travel and facilities relocation costs while complying with various site geometric constraints. The first model, DSLP-GA, is implemented using Genetic Algorithms while the second model, DSLP-ADP, is formulated using Approximate Dynamic Programming. These two models are designed to optimize facilities locations and orientations over construction stages to minimize total layout costs, which include the travel cost of construction resources and the cost of relocating temporary facilities between construction stages. Furthermore, the developed models consider four types of geometric constraints (boundary, overlap, distance, and zone constraints), which can be used to represent site space availability as well as construction operational and/or safety requirements. The performance of these two models is evaluated using two examples to illustrate their capabilities in generating global optimal plans solutions for dynamic site layout planning problems.

Second, a novel model of construction logistics planning (CLP) is developed to enable the integration and simultaneous optimization of critical planning decisions of material procurement and material storage on construction sites. Procurement decision variables are designed to identify the fixed-ordering-periods of each material in every construction stage, while dynamic layout decision variables are designed to identify the locations and orientations of material storage areas and other temporary facilities in each construction stage. The model utilizes Genetic Algorithms to generate optimal material procurement and layout decisions in order to minimize four types of construction logistics costs: material ordering, financing, stock-out, and layout costs. The performance of the developed CLP model is evaluated using an application example that illustrates the model capabilities in: (1) generating optimal procurement decisions that minimize ordering, financing, and stock-out costs while considering site space availability; and (2) generating optimal layout decisions that minimize layout costs while complying with material storage space needs as well as imposed operational and safety geometric constraints.

Third, an innovative multi-objective optimization model for congested construction logistics planning (C2LP) is developed to help planners in utilizing interior building spaces and generating optimal logistics plans that minimize total logistics cost while minimizing the adverse impacts of interior material storage on project schedule. Interior building space is represented as a set of non-identical rooms that can be defined based on project architectural drawings, while exterior space is modeled as a grid of locations with planner-specified fixed spacing. The model utilizes multi-objective Genetic Algorithms to formulate and optimize four categories of decision variables: (1) material procurement that includes fixed-ordering-periods of every material in each stage; (2) material storage plan that includes material storage type, exterior grid location, exterior orientation angle, and/or interior storage location for every material in each stage; (3) temporary facilities site layout that identifies exterior grid location and orientation angle for every temporary facility in each stage; and (4) schedule of noncritical activities that identifies the number of minimum-shifting-days within the total float of each non-critical activity. Interior material storage plans are generated using novel computational algorithms that consider four main types of interior storage constraints: room space capacities, room creation times, room partitioning times, and permissible material interior storage periods. Furthermore, new algorithms are developed to calculate interior and exterior material handling costs as well as shifting of noncritical activities. C2LP model utilizes Genetic Algorithms to generate optimal solutions that represent optimal tradeoffs between the two conflicting objectives of minimizing total logistics costs and project schedule criticality.

Fourth, a prototype automated multi-objective optimization system for construction logistics planning is implemented to support construction planners in generating optimal plans of material logistics and site layout. The system is developed in four main modules: (1) site spatial data retrieval module; (2) schedule data retrieval module; (3) relational database module; and (4) graphical user interface module. The site spatial data retrieval module is designed to facilitate the automated retrieval of site exterior dimensions and building geometric attributes (building footprint, floors, and rooms) from existing IFC-Based Building Information Models of the project. The schedule data retrieval module is designed to obtain the list of construction activities, their relationships, construction materials, and activities material demand from schedule database files that are exported from Microsoft Project. The relational database module is designed to store and integrate project spatial, temporal, and logistics input data considering their interdependencies in order to eliminate data inconsistencies. The user interface module is designed to facilitate data input and reporting of generated optimal material logistics plans.

Fifth, a multi-objective optimization framework is developed to enable construction planners of critical infrastructure projects to plan and optimize the implementation of site physical security systems and layout planning in order to minimize construction security risks and overall site costs. The framework is developed in four main phases: (1) risk identification and system modeling phase to identify security threats, attackers, and targets as well as site and security system geometric representation; (2) security lighting optimization phase to generate optimal tradeoff designs of fence and area lighting systems that consider the conflicting objectives of maximizing lighting performance while minimizing its system cost; (3) security-cost optimization phase to generate optimal site security systems that quantifies and simultaneously minimizes construction security risks and overall site cost; and (4) performance evaluation phase to test and analyze the performance of the proposed framework.

The aforementioned developments of this research study contribute to enhancing the current practices of site layout and material logistics planning and can lead to: (1) increasing the efficiency and global optimality of construction site layout planning; (2) improving construction productivity that can be realized as a result of the early coordination between material procurement and site space planning; (3) enhancing the utilization of interior building spaces for material storage areas while minimizing its possible negative impacts on construction operations and schedules; (4) increasing the security level on the construction sites of critical infrastructure projects; and (5) minimizing contractors site costs that cover the travel cost of resources on construction sites, material logistics, and site security systems.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

1.1 Overview

Planning the site layout of construction projects is a crucial planning task that has a significant impact on construction cost, productivity, and safety. Site layout planning includes identifying site temporary facilities that are needed to support construction activities, determining sizes and shapes of these facilities, and locating them within the boundaries of the construction site. Examples of temporary facilities include tower cranes, fabrication areas, site office trailers, waste disposal containers, and lay-down areas. Construction site space needs to be planned and assigned to these temporary facilities in order to achieve various planning objectives while complying with all operational and safety constraints. For example, congested construction sites impose serious planning challenges for planners because of the scarcity of site space. On the other hand, large construction sites have abundant space availability and accordingly the positioning of site facilities with respect to each other will greatly influence the travel time and productivity of construction equipment and personnel moving between these facilities.

Due to the complexity of the site layout planning problem, construction managers often perform this task using previous experience, ad-hoc rules, and first-come-first-serve approach which can lead to ambiguity and inefficiency (Mawdesley et al. 2002). Site layout planning is a complex problem because of the difficulty of modeling and representing site space availability and demand (Guo 2002), the very large number of possible solutions and layouts of temporary facilities (Yeh 1995, Li and Love 1998), and its conflicting and interdependent planning objectives (Tommelein et al. 1992). As a result, contractors tend to overlook pre-construction planning of site layouts and resort to day-to-day allocation of available site space, which leads to the late detection of space conflicts and the unnecessary relocation of temporary facilities (Cheng and O'Connor 1994).

A number of site layout planning models have been developed over the past three decades to support this important planning task. Existing construction site layout planning models utilize Artificial Intelligence (Yeh 1995, Zhang et al. 2002), Operation Research (Li and Love 1998, AbdelRazig et al. 2005, Khalafallah and El-Rayes 2008), and Geographic Information Systems (Cheng and O'Connor 1996). These models are designed to generate optimal site layout plans that can be categorized in two main approaches: static and dynamic planning. Static layout planning models generate a single site layout that identifies static locations for all temporary facilities in the project. Accordingly, these static models do not consider the dynamic changes of space availability and needs on construction sites. On the other hand, dynamic site layout planning models provide the capability of considering possible reuse of space, relocation of temporary facilities, and the changes in space needs. Existing dynamic site layout planning models divide the project duration into successive stages, where planners identify the available site space and required temporary facilities to support construction activities in each of these stages. Dynamic site layouts are therefore generated in a chronological order and temporary facilities are positioned in each construction stage in such a way that minimizes non-productive site activities, which comprises: (1) material handling and resources travel between site facilities; and (2) layout re-organization by relocating some of the facilities that were positioned in previous stages.

1.2 Problem Statement

Despite the contributions of existing site layout planning models, they have a number of limitations, as shown in Figure 1.1. Accordingly, the identified research needs in this study are designed to focus on five main thrusts: (1) investigating and enabling global optimization of dynamic site layout planning; (2) integrating material procurement and site layout planning in a construction logistics planning model; (3) exploring and enhancing the utilization of interior building spaces for material storage areas on congested construction sites; (4) enabling automated retrieval and integration of all necessary data of construction logistics and site layout planning from available design and planning documents; and (5) modeling and considering security needs and constraints during the construction of critical infrastructure projects.

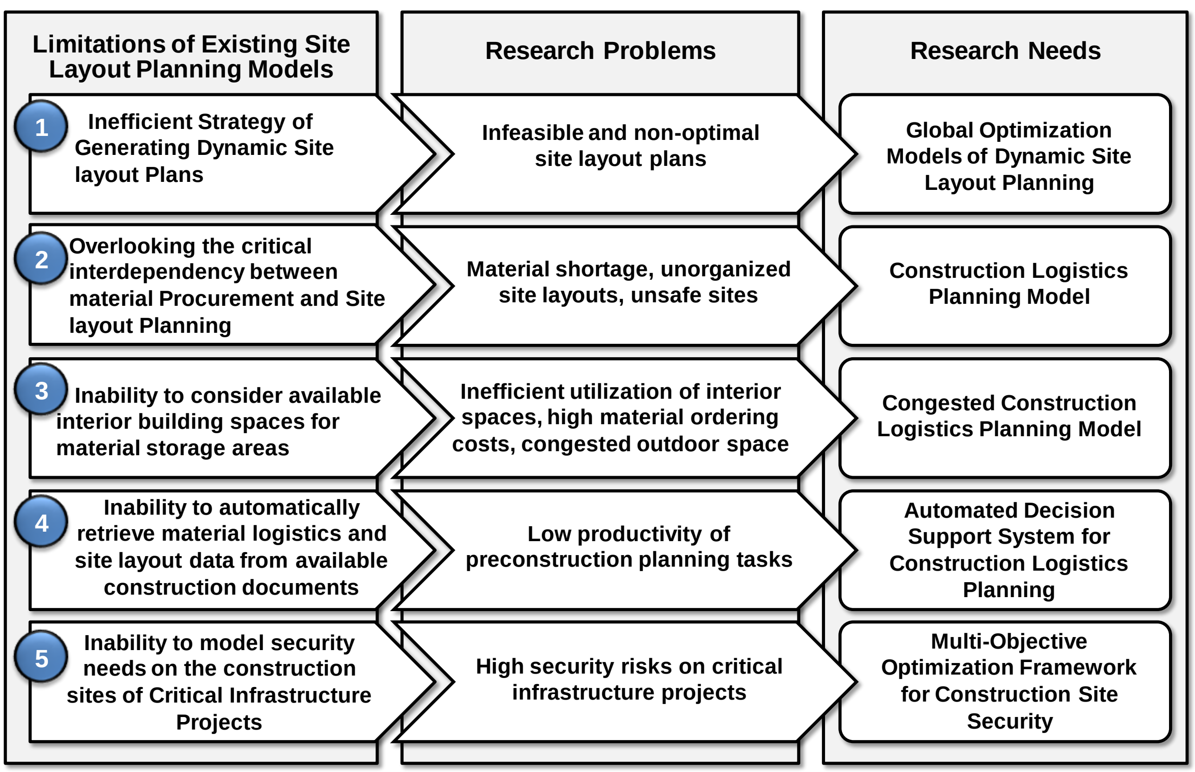


Figure 1.1 Limitations of Existing Site Layout Planning Models and Research Needs

First, existing dynamic site layout planning models utilize an inefficient chronological strategy to generate dynamic layout plans that may result in infeasible or non-optimal solutions (Zouein and Tommelein 1999). This chronological strategy does not consider the future effects of layout decisions in early construction stages on the layout quality of subsequent stages. This often results in non-optimal dynamic layout plan or, moreover, infeasible layout plans in later construction stages, as shown in Figure 1.2 that represents a two-stage example project with three temporary facilities: tower crane, fabrication area, and storage area. The construction in the first stage needs the tower crane and the fabrication area, while the second stage needs the storage area in addition to the tower crane. Existing DSLP models handle this example problem by optimizing the site layout of the first stage followed by the site layout of the second stage. The site layout of the first stage is generated by positioning the tower crane in its optimal location in this stage as shown in Figure 1.2-a. Based on the layout generated in the first stage, existing models will not be able to find a feasible location for the storage area in the second stage because of the lack of space for it. It should be noted that the tower crane cannot be relocated in the second stage because it is both time and cost consuming (i.e. it is infeasible to relocate it). Accordingly, there is a need to have new DSLP models that overcome the inefficiency of current models by considering the effects of first stage layout decisions on the layouts of subsequent stages. By having such look-ahead capabilities, the tower crane can be placed in another location rather than its optimal one to provide enough space for the storage area in the second stage, as shown in Figure 1.2-b.

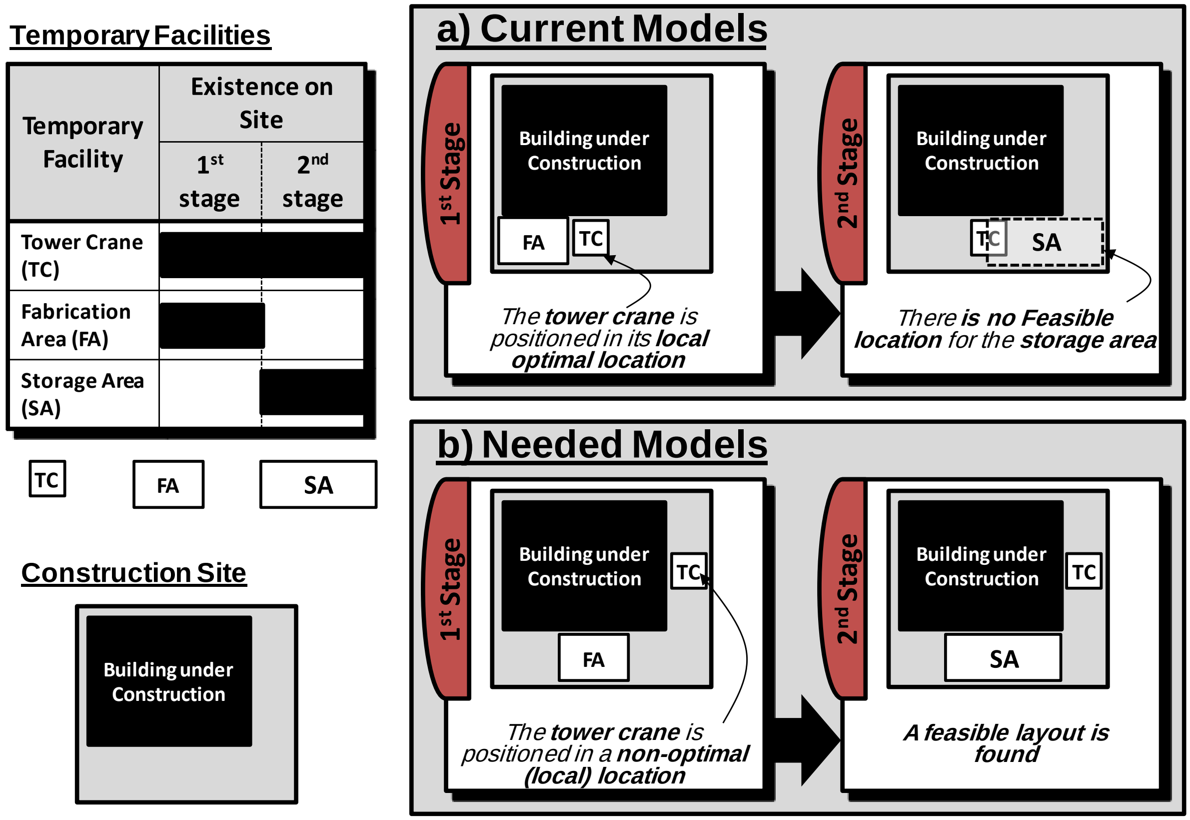


Figure 1.2 Limitations of Previous Models of Dynamic Site Layout Planning

Second, the integration and coordination between the decisions of material procurement and material storage onsite is vital to avoid major site problems and increase the efficiency of these two tasks. Existing models and decision support systems of material procurement (Horman and Thomas 2005; Polat and Arditi 2005; Subsomboon and Christodoulou 2003; Tserng et al 2006; Polat et al 2007) focus on procurement decisions without considering the impact of material storage space availability on dynamic construction site layouts. On the other hand, existing models of dynamic site layout planning focus on site layout decisions without considering the impact of material procurement decisions on inventory levels and storage space needs. Overlooking these critical interdependencies between material procurement and site space availability can lead to significant adverse impacts on project performance including material shortages, improper storage, poor and unsafe site layout, and productivity losses (Bell and Stukhart 1987; Thomas et al 1989; Jang et al 2007). Accordingly, there is a pressing research need to develop new optimization models of construction logistics planning (CLP) model that is capable of integrating and optimizing material procurement and site layout planning decisions while considering their inherent interdependencies.

Third, congested construction sites (e.g. urban building projects) often have insufficient exterior space to accommodate all needed temporary facilities and material storage areas (Riley and Sanvido 1995). Accordingly, interior spaces of buildings under construction often need to be used for material storage while exterior space is left for site temporary facilities such as office trailers and tower cranes (Elbeltagi et al. 2004). Existing site layout planning models, however, do not support the utilization of interior spaces due to a number of challenges, including the complexity of interior space modeling, and the dynamic constraints of interior space availability and capacities. Furthermore, the sequence of indoor construction activities should be integrated with interior material storage plan by optimally shifting noncritical construction activities in order to maximize the availability of interior storage spaces while minimizing any adverse impacts on schedule criticality (Thomas et al. 2005). Inefficient utilization of interior spaces on congested construction sites leads to: (1) crowded and overloaded exterior site spaces that negatively impact construction productivity and safety; and (2) high material ordering and delivery costs because of site limited storage capacity that results in frequent small material deliveries with underutilized delivery trucks. Therefore, there is an urgent and pressing need for advanced logistics planning models that facilitate the optimal utilization of interior spaces for material storage areas and temporary facilities in order to minimize construction logistics costs while minimizing construction schedule criticality.

Fourth, construction planners are required during site layout and logistics planning to provide large amount of input data that describe site spatial information, interior building spaces, and construction schedule. The manual identification of these input data becomes a cumbersome and time consuming process especially in large and complex construction projects. These input data are, however, generated and readily stored in existing design and planning documents, including: (1) construction schedule that identifies activity durations, activity times, construction materials and their assignments to activities; (2) building information models (BIM) that store all relevant spatial information of the construction site as well as the interior spaces of the building under construction; and (3) logistics databases that include temporary facilities and suppliers data. As such, there is pressing need to study and develop a novel multi-objective automated decision support system that facilitates seamless retrieval and integration of project spatial, temporal, and logistics data for the optimal logistics planning on congested construction sites.

Fifth, contractors are required by Federal regulations to secure the construction sites of critical infrastructure projects to minimize security risks during the construction phase. Critical infrastructure systems are complex connected networks of vital public facilities that their malfunction or destruction would negatively affect national defense or economic security (PEO 1996). As a result, a national program was established and named Critical Infrastructure Protection (CIP) to manage the protection of critical infrastructures and resources (HSPD 2003). The National Institute of Standards and Technology (NIST) and the

Construction Industry Institute (CII) also recognized that the effectiveness and efficiency of security of these critical infrastructure projects are influenced by decisions made during planning and construction phases (NIST 2004, CII 2005). Several Federal regulations have been produced to establish security requirements and arrangements during the construction of critical infrastructure projects such as construction security certification program of the Department of State (FAM 1994, FAM 1997, FAM 2002), Federal Aviation Administration (FAA) recommended security guidelines (FAA 2001), and the National Industrial Security Program (PEO 1993). Few research studies investigated the implementation of security measures during the construction phase of critical infrastructure projects (Branch and Baker 2007; Khalafallah and El-Rayes 2008).

Although previous regulations and existing research studies addressed security needs and considerations during the construction phase, they all focused on the implementation of physical security measures without considering the mutual impacts between construction site layout and the performance of site security system. Accordingly, there is an urgent need to support current construction security standards by studying and modeling the mutual impacts between construction site layout design and the effectiveness of the implemented security measures. There is also a need to develop a novel multi-objective optimization framework to optimize the decision of construction site security system and layout planning while considering the conflicting objectives of minimizing construction security risks and minimizing overall site cost.

1.3 Research Objectives

The primary goal of this study is to develop novel optimization models and systems that enable the optimization of dynamic site layout and material logistics planning during the construction of critical infrastructure systems. This primary goal is broken down into the following objectives, along with their relevant research questions and hypotheses:

<u>Objective 1:</u>

To formulate and develop innovative models of dynamic site layout planning (DSLP) in order to overcome the inefficiency of existing models and provide to the capability of generating global optimal solutions of DSLP problems by considering the effects of first stage layout decisions on the layouts of subsequent stages. The formulation of these models needs to: (i) represent the dynamic environment on construction sites and various characteristics of different construction facilities; (ii) optimize site layout plans dynamically over the project duration to minimize travel costs of contractor's resources onsite as well as any additional costs of relocating onsite temporary facilities; and (iii) comply with different geometric, operational, and safety constraints and restrictions.

<u>Research Questions:</u>

(a) What are the decision variables of dynamic site layout planning that have a critical impact on the travel cost of construction resources and relocation costs of temporary facilities? (b) How can travel and relocation costs be objectively quantified and minimized? (c) What are the constraints imposed on the decision variables of dynamic site layout planning to represent construction operational and safety restrictions and requirements? and (d) What are the global optimization tools and approaches that can be used to generate global optimal dynamic site layout plans?

Hypothesis:

New optimization models of dynamic site layout planning can be developed to search for and generate global optimal solutions while satisfying construction operational constraints by having look-ahead capabilities to consider the effects of first stage layout decisions on the layouts of subsequent stages.

Objective 2:

To develop a new optimization model of construction logistics planning (CLP) that is capable of integrating and optimizing the critical planning decisions of material procurement and material storage on construction sites. The development of this new model needs to: (i) represent all decision variables of material procurement and onsite storage layout as well as dynamic site layout decisions for all the temporary facilities on site; (ii) model the interdependencies between the decision variables of materials procurement and onsite storage; (iii) objectively represent the onsite materials inventory system that models the material needs and handling as well as the demand fulfilling mechanism; (iv) formulate and optimize the impact of the decision variables on material procurement and site layout costs; and (v) dynamically comply with all practical constraints on the site space availability and material supply capacity.

Research Questions:

(a) What are the relevant costs that are affected by the decision variables of material procurement and storage onsite? (b) How can the onsite material inventory be represented and what are the considered decision variables? (c) What are the practical constraints that need to considered and complied with during the material procurement decisions to represent the site space and suppliers limitations? (d) How to model the interdependencies between the decision of material procurement and site layout planning? and (e) How to quantify and minimize the costs of material procurement and onsite material storage and layout?

Hypothesis:

New optimization models can be developed to integrate and simultaneously optimize critical planning decisions of material procurement and site layout planning by modeling the inherent interdependencies between these decision variables and quantifying and minimizing their impact on procurement and layout costs.

Objective 3:

To develop a novel multi-objective optimization model that is capable of modeling and utilizing interior and exterior spaces to generate optimal logistics plans for congested construction sites. The formulation of this model should enable: (i) representing interior and exterior spaces on congested construction sites; (ii) identifying and modeling spatio-temporal relationships and constraints between interior construction activities, spaces, and material storage areas; (iii) modeling the impact of construction activities schedule on the availability of interior building spaces for material storage; (iv) quantifying logistics costs of the supply and the storage (interior and exterior) of construction materials; and (v) generating optimal material logistics plans that provide optimal tradeoffs between minimizing material logistics costs and minimizing project schedule criticality.

Research Questions:

(a) How can interior building spaces be represented in an efficient and practical way that minimizes its computational requirements? (b) What are the critical constraints that need to considered and complied with during the utilization of interior building spaces that are imposed by indoor construction schedule and capacities of interior spaces? (c) How to optimally assign interior spaces to material storage areas and temporary facilities considering spatial capacities as well as creation and partition times of interior spaces? (d) What are the relevant decision variables that need to be considered to represent the execution times of noncritical activities? (e) How to quantify indoor material handling as well as the criticality of construction schedule due to material procurement, site layout, and schedule of indoor construction activities? and (f) How to optimize logistics planning of congested construction sites in order to simultaneously minimize total logistics costs and minimize the criticality of construction schedule?

Hypothesis:

A new multi-objective optimization model can be formulated to optimize logistics plans of congested construction sites that is capable of considering both interior and exterior spaces and simultaneously minimizing logistics costs and schedule criticality.

Objective 4:

To develop a multi-objective automated system for construction logistics optimization that enables seamless retrieval and integration of project spatial, temporal, and logistics data as well as generating and reporting optimal plans of material procurement and site layout. The development of the proposed system needs to: (i) enable the retrieval of exterior and interior spatial data of the construction site by parsing IFC (Industry Foundation Classes) files of existing building information model (BIM) of the project; (ii) facilitate the input of construction schedule data, such as project network and material demands, by integrating available schedule files of a construction planning software package, Microsoft Project; (iii) support the seamless integration of previously defined data by enabling the planners to define various types of spatio-temporal linkage and store all input data into a relational database; (iv) enable efficient and effective optimization of material procurement and site layout planning through the implementation of robust computational algorithms; and (v) provide a graphical user interface that facilitates data input and informative visualization of optimization results.

Research Questions:

(a) What is the best architecture to input, store, retrieve, process, and visualize the data and results of the proposed prototype system? (b) How to retrieve schedule and spatial data from existing electronic files of Building Information Models and construction planning software packages? and (c) How can construction planners best view and evaluate the optimal tradeoffs generated by the multi-objective optimization model?

Hypothesis:

A new automated decision support system can be developed to enable seamless retrieval and integration of project spatial, temporal, and logistics data as well as generating and reporting optimal plans of material procurement and site layout.

Objective 5:

To develop a multi-objective optimization framework for planning construction site layouts and site security systems of critical infrastructure projects. The formulation of this framework should enable: (i) modeling the construction site as a dynamic security system that includes security targets, boundaries, countermeasures, and potential intruders as well as modeling the dynamic construction site space availability and needs that change over time; (ii) modeling the impact of site layout and space planning on the performance of the site security system; (iii) quantifying the impact of the implemented security and site layout measures on the performance of the security system using newly developed metrics and methodologies; (iv) satisfying practical constraints and requirements that are imposed by Federal security regulations and specifications; and (v) generating optimal tradeoffs between the optimization objectives of minimizing security risks and minimizing overall site cost.

Research Questions:

(a) How to represent and model the security system on the construction sites of critical infrastructure projects? (b) What are the interdependencies and mutual impacts between site layout planning and the design of the construction site security system? (c) What are the decision variables of site security system design that have a significant impact on construction logistics costs? (d) How to quantify the performance of site security system as well as overall site cost that includes site layout and security costs? and (e) How to optimize construction site layout and security design in order to simultaneously minimize construction security risks and overall site costs.

Hypothesis:

A new multi-objective optimization framework can be developed to optimize site layouts and security systems of critical infrastructure projects by modeling the interdependencies between layout and security decision while optimizing their impacts on the objectives of minimizing construction security risks as well as overall site costs.

1.4 Proposed Methodology

In order to achieve the aforementioned objectives, the research work in this study is organized into five major research tasks that are designed to: (1) perform a comprehensive literature review of the latest research developments and practices of site layout planning, material procurement, and security system design; (2) formulate robust global optimization models of dynamic site layout planning; (3) develop a new construction logistics planning model that integrates the decisions of material procurement and site layout planning; (4) develop a multi-objective optimization framework for planning construction site layouts and site security systems of critical infrastructure projects; and (5) Implement an automated decision support system that integrates the developments of this study, as shown in Figure 1.3.

1.4.1 Task 1: Literature Review

This task is designed to investigate the latest research developments in the main domains of this study including dynamic site layout planning, material procurement, and design of security systems. This research task is accordingly divided into the following subtasks:

1. Review all existing research studies in the area of dynamic site layout planning;
2. Investigate previous research developments in materials procurement, supply, and onsite storage;
3. Examine available Federal regulations and requirements relevant to construction site security of critical infrastructure projects;
4. Explore previous models and tools of security systems design and engineering; and

5. Survey all available tools of multi-objective and global optimization and examine their applicability for integrated material procurement and site layout planning in critical infrastructure construction projects.

1.4.2 Task 2: Dynamic Site Layout Planning Models

The purpose of this task is to formulate and develop robust models of dynamic site layout planning that overcome the inefficiencies of current DSLP models. The research work in this task is divided into the following subtasks:

1. Explore different types of temporary facilities in construction sites and the extent of their space requirements and relocation possibilities;
2. Develop objective metrics that enable the quantification and minimization of site layout costs;
3. Investigate and model all decision variables of dynamic site layout planning that contribute to the optimization objective;
4. Identify and model various site layout constraints that affect construction safety and operational requirements;
5. Implement the formulated optimization model using robust global optimization approaches; and
6. Validate, verify, and analyze the performance of developed global optimization models of dynamic site layout panning.

1.4.3 Task 3: Construction Logistics Planning Model

The goal of this research task is to develop a new optimization model of construction logistics planning (CLP) that is capable of integrating and optimizing critical planning decisions of material procurement and material storage on construction sites. The efforts in this task are organized in the following subtasks:

1. Review all cost components of construction material procurement and logistics that cover the material supply process from the supplier till the incorporation into the finished structure;
2. Investigate and formulate all decision variables of material procurement that affect material procurement costs as well as site layout costs;
3. Analyze and represent interdependencies between the decisions of material procurement and the site layout plan;
4. Formulate quantitative metrics to model construction logistics costs as a function of both material procurement and layout planning decisions;
5. Implement an optimization model that integrates the decisions of material procurement and site layout in order to minimize construction logistics costs; and
6. Evaluate, verify, and analyze the performance of the developed optimization model.

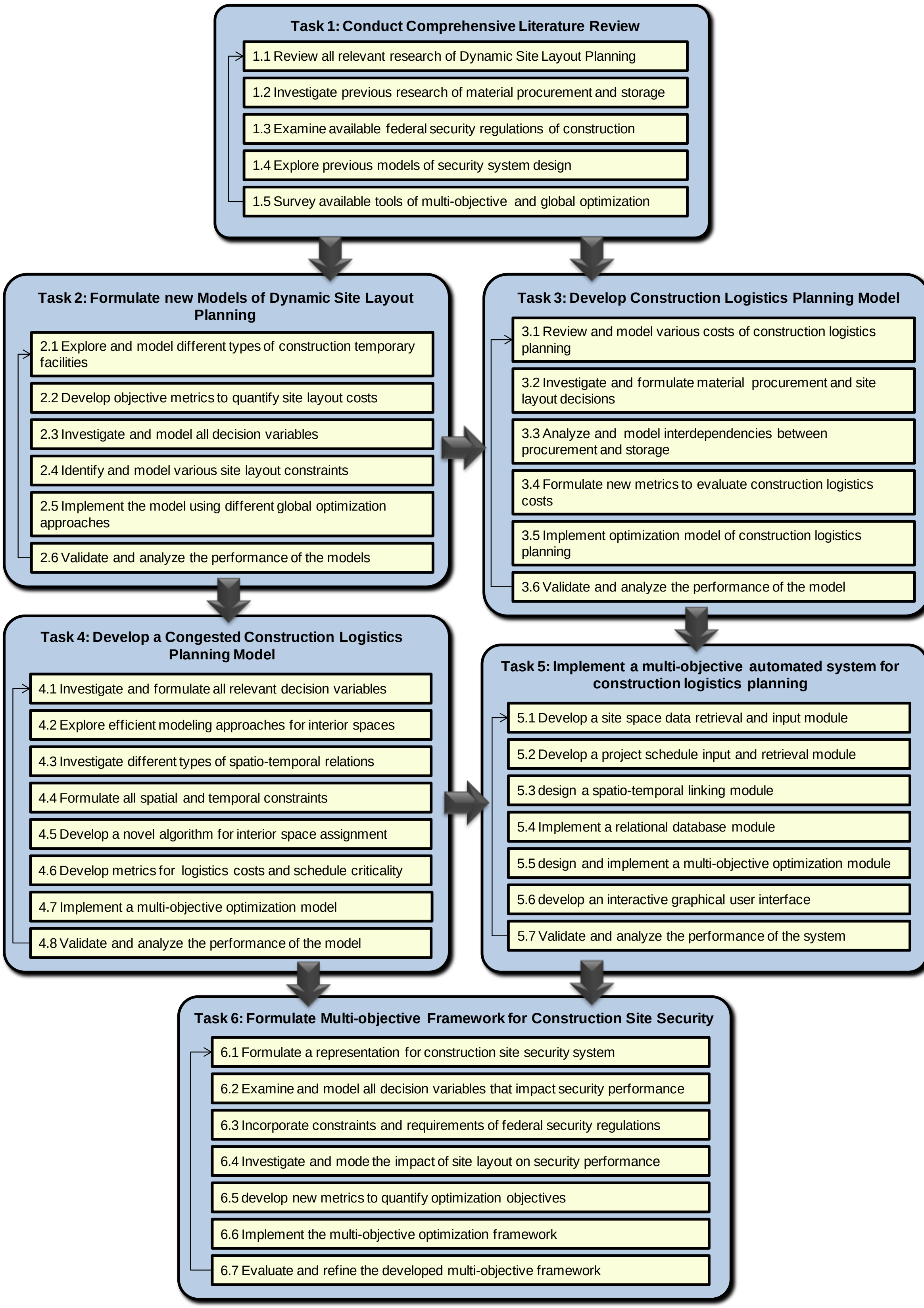


Figure 1.3 Research Methodology and Tasks

1.4.4 Task 4: Congested Construction Logistics Planning Model

The goal of this research task is to develop a new multi-objectives optimization model that is capable of modeling and utilizing interior and exterior spaces in order to generate optimal logistics plans for congested construction sites. This research tasks is organized in the following subtasks:

1. Investigate and formulate all relevant decision variables of material procurement, interior material storage, exterior site layout, and indoor construction schedule that affect total logistics cost and project schedule criticality;
2. Explore efficient and practical modeling approaches that can be used to represent interior building spaces with minimal computational efforts;
3. Investigate different types of spatio-temporal linkage to represent interrelationships between the schedule of construction activities and interior spaces;
4. Examine and formulate all practical constraints that impact the decisions of utilizing interior spaces for material storage areas and temporary facilities;
5. Develop a novel algorithm of interior spaces assignment to material storage areas and temporary facilities that considers spatial capacities as well as creation and partition times of interior spaces;
6. Formulate quantitative metrics to model material procurement and storage costs as well as project schedule criticality of congested logistics planning;
7. Implement a multi-objective optimization model that integrate material procurement, interior material storage, exterior site layout, and shifting of noncritical activities to simultaneously minimize total logistics costs and project schedule criticality; and

8. Evaluate, verify, and analyze the performance of the developed multi-objective optimization model.

1.4.5 Task 5: Prototype Multi-objective Automated System for Construction Logistics Planning

The goal of this research task is to develop a multi-objective automated system of construction logistics optimization that enables seamless retrieval and integration of project spatial, temporal, and logistics data as well as generating and reporting optimal plans of material procurement, site layout, and interior material storage. The efforts in this task are organized in the following subtasks:

1. Develop a site space data retrieval and input module that is capable of parsing IFC files of project's existing BIM models to extract spatial attributes of the construction site and interior building spaces;
2. Develop a project schedule input and retrieval module that facilitates integrating existing schedule data from Microsoft Project, in order to identify construction activities and materials demand;
3. Design a spatio-temporal linking module that facilitates the integration of spatial and schedule data in order to define different interrelationships between construction activities and interior spaces, such as workspaces and floor partitioning times;
4. Implement a relational database module that stores input data and optimization results of construction site layout, material procurement, and interior material storage plans;
5. Design and implement a multi-objective optimization module that quantifies and simultaneously optimizes construction logistics costs and schedule criticality of congested construction projects;

6. Develop an interactive graphical user interface to enable input, retrieval, and visualization of data and optimization results; and
7. Verify, validate, and refine the performance of the developed automated system.

1.4.6 Task 6: Construction Site Security Framework

The purpose of this research task is to develop a multi-objective optimization framework for planning construction site layouts and site security systems of critical infrastructure projects. This research tasks is organized in the following subtasks:

1. Provide a formulation of construction site security system that encompasses security targets, boundaries, countermeasures, and potential attackers;
2. Examine and formulate the decision variables of construction site layout planning and security system design that directly affect security performance and logistics costs;
3. Incorporate security and layout requirements and constraints of available federal security regulations and guidelines;
4. Investigate and model the impact of site layout decisions on the performance of site security system;
5. Formulate new metrics that quantitatively estimate the optimization objectives of minimizing construction security risks and overall site costs as a function of the decision variables of both security system design and site layout planning;
6. Implement optimization decision variables, objectives, and constraints in a multi-objective optimization framework; and
7. Evaluate, verify, and analyze the performance of the developed framework.

1.5 Significance of Proposed Research

The developments of this research study are expected to have significant contributions in: (1) optimizing site layout and space planning; (2) enhancing construction material management; (3) enhancing security of critical infrastructures; (4) improving construction productivity; and (5) mitigating construction conflicts and disputes.

Impact on Site Planning: This research study will result in global optimization models of dynamic site layout planning that overcome the inefficiencies of existing models (Zouein and Tommein 1999) to generate optimal plans for safer and more productive construction sites. The proposed models utilize global optimization approaches and tools to consider the impact of layout decisions in early construction stages on the quality of layout plans in future stages. Furthermore, these models are designed to consider all relevant characteristics of construction facilities, such as space dynamic needs and relocation feasibility, as well as various operational and safety layout constraints.

Impact on Material Management: the efficiency of construction material management can be significantly improved by enhancing the interface and coordination between material procurement and site activities (Vrijhoef and Koskela 2000) as well as early involvement of material suppliers in construction planning (Kini 1999). The proposed model in this study of construction logistics planning optimizes the interface between the decisions of material procurement and site planning in order to avoid materials shortage, double handling of materials, and unnecessary transportation costs. Furthermore, the model facilitates the early involvement of material vendors and suppliers in the planning of material procurement and onsite storage by sharing their input and information such as delivery options, capacities, and costs.

Impact on Construction Productivity: This research study holds a strong potential to improve construction productivity by generating efficient construction site layouts and alleviating the current negative impacts of material shortage on productivity. First, efficient site layout plans improve construction productivity by minimizing non-productive times of construction crews to handle materials from storage areas to activities areas (Tam et al. 2001). Also, the proposed layout planning models are designed to consider various types of safety and operational constraints that would result in a safer work environment for more productive crews. Second, this study proposes integrating the decisions of material procurement and site layout planning to consider existing interdependencies and maximize the coordination between these planning tasks. As recognized in previous research studies (Bell and Stukhart 1987; Thomas et al 1989; Jang et al 2007), the lack of this coordination between material procurement and site layout planning often results in major productivity problems such as material shortages, improper storage, and unsafe site conditions. Furthermore, optimizing the decisions of material procurement and supply is one of the potential approaches of improving construction productivity (Arditi and Mochtar 2000; Thomas and Sanvido 2000).

Impact on Infrastructure Security: Despite the significant impact of construction security on the vulnerability of critical infrastructure projects (NIST 2004, CII 2005), few research studies investigated the implementation of security measures during the construction phase of critical infrastructure projects (Branch and Baker 2007). This study is designed to fill this research gap by developing a multi-objective optimization framework to help construction planners to minimize construction security risks as well as overall site costs. The proposed framework has the capabilities of capturing the unique dynamic environment of construction sites and impacts of site layout planning on security system performance.

Impact on Construction Conflicts: This study is expected to support construction managers in mitigating conflicts and disputes with project owners and material suppliers. First, the proposed construction security framework is designed to generate optimal tradeoff solutions that provide alternative plans to simultaneously minimize security risks and overall site costs. Accordingly, construction managers and project owners (or security officers) can select a solution from these optimal tradeoffs that best fit the budget and targeted security level of the project. Furthermore, the proposed security framework provides a set of new metrics to quantify and evaluate the performance of deployed security measures considering site layout impacts. Second, this study proposes a new model of construction logistics planning that help in optimizing the coordination and collaboration between site planning and material procurement. This coordination requires the early involvement of material vendors and suppliers in the planning and design phase, which alleviates possible future conflicts that may rise in the phase of actual construction.

1.6 Report Organization

The organization of this report and its relation with research objective, tasks, and deliverables is described as follows:

Chapter 2 presents a comprehensive literature review of all relevant research and practices in dynamic site layout planning, procurement and supply of construction material, regulations and guidelines of construction site security of critical infrastructure projects, and various tools and approaches of global and multi-objective optimization.

Chapter 3 discusses the development of global optimization models of dynamic site layout planning that are designed to minimize site layout costs. A detailed description is provided to cover the representation and formulation of optimization decision variables, objective functions, constraints, and the implementation of the optimization model using two different approaches of global optimization. The performance of these models is verified and investigated using a set of application examples.

Chapter 4 presents the development of a construction logistics planning model that integrates the decisions of material procurement and dynamic site layout planning. This chapter introduces the development of new metrics to quantify and minimize different costs of construction logistics planning that are impacted by procurement and layout decisions. The developed model is implemented and evaluated using an application example to show its capabilities in optimizing construction logistics planning.

Chapter 5 discusses the development of a congested construction logistics planning model that models and utilizes interior and exterior spaces in order to generate optimal logistics plans for construction sites with scarce exterior spaces. A detailed description is provided to cover the formulation of the following decision variables: material procurement, interior material storage, shifting of noncritical activities and exterior site layout planning. Furthermore, the chapter presents an analysis of the impact of these decision variables on the optimization objectives of minimizing logistics costs and project schedule criticality. The performance of the developed model is illustrated and validated using an application example of 10-storey building project on a congested construction site.

Chapter 6 illustrates the implementation of a prototype multi-objectives optimization system for construction logistics planning by covering in details the development of its main components: site spatial data retrieval module, project schedule data retrieval module, relational database module, and graphical user interface.

Chapter 7 discusses the development of a multi-objective optimization framework for planning construction site layouts and site security systems of critical infrastructure projects. This chapter describes the representation of construction security systems in the developed framework; the decision variables of both site security system design and layout planning; the development of new metrics to quantify and minimize construction security risks and overall site costs; the implementation of the framework using a multi-objective optimization tool that optimizes the tradeoff between minimizing construction security risks and overall site costs; and performance evaluation and analysis of the developed framework using an application example.

Chapter 8 presents the conclusions, research contributions, and recommended future research of the present study.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

An extensive literature review was conducted to demonstrate relevant knowledge and existing research to establish a solid starting point to pursue the proposed study. This chapter provides a brief summary of the reviewed literature of: (1) available models and decision support tools of dynamic site layout planning, (2) material procurement planning and inventory control, (3) material management practices and research in the construction industry; (4) construction security regulations for critical infrastructure projects, (5) decision support models of physical security design and engineering, and (6) multi-objective optimization.

2.2 Dynamic Site Layout Planning Models

Dynamic site layout planning (DSLP) is a pre-construction managerial task that treats construction site space as a constrained recourse by assigning it to site temporary facilities (i.e. offices, storage areas, and workshops) in a timely manner. The dynamic assignment of site space in DSLP is done to achieve several objectives such as minimizing nonproductive time and cost (i.e. material handling and relocation) and/or maximizing safety. This planning task comprehends dividing the project duration into a set of successive stages that represent major construction phases and different levels of site space needs. Accordingly, temporary facilities are identified in each stage and the site layout is dynamically planned in order to optimize various objectives of travel distance, safety, and/or security. DSLP becomes highly effective in congested construction sites by considering construction dynamic environment through the assignment of released spaces to new temporary facilities and relocating existing facilities to better locations.

Despite its potential benefits, planners tend to underutilize DSLP in project planning stage because of its complexity especially in large-scale and confined construction projects (Mawdesley et al. 2002). Therefore, automated models of DSLP that utilizes Operations Research (OR), optimization techniques, and visualization were developed in order to help planners and contractors in this complex planning task. Available models of dynamic site layout planning can be classified into five main categories: (1) hybrid linear programming, (2) Genetic Algorithms (GA), (3) ant colony optimization (ACO), (4) geographical information system (GIS); and (5) four-dimensional (4D) visualization.

2.2.1 Hybrid Linear Programming

Zouein and Tommelein (1999) developed a hybrid model that utilizes heuristics, constraint satisfaction, and linear programming (LP) to optimize the layout of temporary facilities in order to minimize transportation and relocation costs. Construction temporary facilities are represented as rectangles with their relocation costs and distance-based travel cost among them defined using dimensionless weights. This hybrid model generates the optimal position and orientation of every temporary facility in each stage in a stepwise approach through three steps: (1) selecting heuristically the facility to be positioned based on a set of ad-hoc rules that consider the importance of the facility in terms of its travel and/or relocation weights; (2) computing a set of feasible positioning decisions for the facility using a constraint satisfaction and propagation algorithm; and (3) finding the optimal option from this set of feasible decisions using linear programming so as to minimize travel and relocation costs.

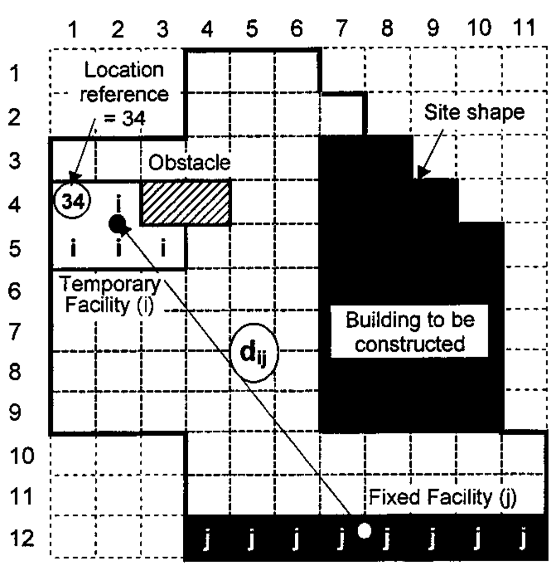
The solutions generated are path-sensitive because layout decisions are generated in a stepwise approach that is significantly affected by the imposed ad-hoc and heuristics rules (Zouein and Tommelein 1999). Furthermore, the positioning of every facility does not consider its future impacts on subsequent decisions of other facilities in the same stage as well as in next stages.

2.2.2 Genetic Algorithms

Genetic Algorithms are search techniques that mimic the metaphor of natural biological evolution to search for global optimum solutions of complex problems (Goldberg 1989, Deb et al. 2000). GA utilizes a set of biological evolution operations such as inheritance, selection, crossover, and mutation to enhance the quality of a set of solutions through evolution over a number of generations. A solution to a given problem is represented in the form of chromosome string, where each chromosome element (gene) refers to a specific decision variable of the problem. The algorithm starts with a random population of solutions, where the fitness of each solution is evaluated using an objective function. Accordingly, the fittest solutions are chosen through a specific selection mechanism to exchange their information (using crossover and mutation operations) to produce better offspring. This process of selection, crossover, and mutation is repeated for a specific number of iterations (generations) or until a predetermined convergence criteria is satisfied.

Researchers implemented Genetic Algorithms to optimize large and complex problems of dynamic site layout planning. Osman et al (2003) proposed a CAD-based optimization model that integrates the graphical capabilities of CAD software applications with the robust search and optimization tools of GA to generate optimal dynamic layout plans. First, the proposed model utilizes CAD to perform two main functions: space detection and constraint satisfaction. Space detection is performed before the GA optimization to divide the site into a set of grid locations available for assignment of temporary facilities. Constraints satisfaction is performed during the GA optimization to check the feasibility of every temporary against site and overlap constraints. Second, GA is used to optimize the dynamic layout planning for the whole project duration by solving the layout problem of every construction stage separately considering minimizing resource travel cost and facilities relocation cost. This means that the whole problem of dynamic site layout planning is divided into a set of T static layout problems for T construction stages. These T static layout problems are solved in a stepwise fashion for T iterations, where a different stage is selected to be the initial stage whose optimal layout is generated first. Despite the potential benefits of this approach over the model of Zouein and Tommelein (1999), it has the following limitations: (1) it still may result in non-optimal or infeasible solutions as the local optimal layout of each stage is generated for each stage without the consideration of its impact on the layout quality of other stages; and (2) it is computationally exhaustive for large scale problems of dynamic site layout planning.

Elbeltagi et al. (2004) implemented genetic algorithm in a spreadsheet-based optimization model of dynamic site layout planning that enable the simultaneous minimization of both travel cost and safety as one integrated function. Commercial spreadsheet software is used as the platform of the developed model that comprehends inputting, optimization, and outputting modules. Using spreadsheets, user can define construction site and temporary facilities as irregular shapes using sheet (grid) cells as modeling blocks, as shown in Figure 2.1. The size of each sheet cell is calculated as the greatest common divisor (GCD) of the areas of all site facilities. Interactions between site facilities are represented using seven levels of closeness relationship weights, as shown in Figure 2.1, to model planner's operational and safety preferences. Assigning a high value of closeness weight to a pair of site facilities refers to the necessity to place them as close as possible to reflect heavy flow of construction resources. On the hand, assigning a low value of closeness weight refers to the necessity to place the facilities apart from each other to reflect any safety concerns. Using these closeness weights, site layout is optimized utilizing GA to minimize the weighted sum of all travel distances between site facilities. The proposed model Elbeltagi et al. (2004) doesn't consider the relocation cost of facilities as any changes in their layout decisions over project stages are not reflected in the objective function. Furthermore, the model doesn't consider the tradeoff between minimizing layout cost and minimizing safety as these two objectives are considered in one dimensionless objective function.



Closeness Relationship	Weight
Necessary to be close	10^3
Better to be close	10^2
May be close	10^1
Indifferent	0
May be apart	-10^1
Better to be apart	-10^2
Necessary to be apart	-10^3

Figure 2.1 Representations of Site Geometry and Closeness Relationship (Elbeltagi et al. 2004)

2.2.3 Ant Colony Optimization

Ant Colony Optimization (ACO) is a search technique, developed by Dorigo et al (1996), based on the phenomena that the ants are able to iteratively find the shortest path between their nest and a food source. This is done through pheromone trails that the ants leave behind as a mean of indirect communication. ACO is an iterative technique that mimics the ants behavior in converging to the shortest path (the optimal solution) through the gradual compilation of the pheromone trail. The algorithm starts by randomly generating a set of "artificial ants" that represent different solutions or paths. Each ant is evaluated against an objective function, which determines the change of pheromone concentration on its path. Iteratively, the ants are sent into different paths (changing the values of the decision variables) considering the pheromone concentrations from previous iterations. Accordingly, positive feedback through iterations would lead that all ants will choose a single path that represents the optimal solution. AbdelRazig et al (2005) implemented ACO in an optimization model of DSLP that minimizes travel and relocation costs. They modeled dynamic site layout planning as a quadratic assignment problem (QAP) that assumes that the number of predetermined site locations should be equal to the number of required temporary facilities. If the number of site locations is larger than the number of temporary facilities, then a set of "dummy" facilities is added to have equal numbers of positions and facilities. This modeling approach is significantly time consuming especially in large construction sites that have large number of possible positions compared to the number of utilized temporary facilities.

2.2.4 Geographical Information Systems

Geographical information system (GIS) is a technological tool that integrates hardware, software, and data to help in modeling, storing, analyzing, and displaying various kinds of geographically referenced information (GIS 2009). GIS helps planners and managers to investigate relationships, patterns, and trends between information and produce informative results in the form maps, reports, and charts. Cheng and O'Connor (1994 and 1996) developed a GIS-based model (ArcSite) of dynamic site layout planning that captures layout planning knowledge and support planners in designing construction site layout. First, ArcSite comprehends a knowledge base that includes expert's knowledge and experience of site layout planning obtained from research literature and companies manuals. The knowledge base component of Arcsite is designed to perform four main operations: data inputting, knowledge acquisition, knowledgebase processing, and reasoning explanation. Second, ArcSite helps planners in designing site layout plans through site spatial analysis and quantification of layout decision. A constructive placement procedure is implemented to select and place site temporary facilities one at a time considering available locations and their qualities. During this iterative process, the system generates the potential locations for every facility using the concept of searching by elimination. The quality of each of these potential locations is evaluated using a proximity index that considers the travel frequency and attract/repel relationships between site facilities. Similar to previous models of dynamic site layout planning, this constructive placement procedure adopted in ArcSite doesn't consider the implications of early layout decision on the quality of subsequent ones.

2.2.5 4D Visualization

Four-dimensional (4D) visualization models were developed as visual decision support tools that help construction planners in dynamic site layout planning. As shown in Figure 2.2, previous 4D visualization models (Zhang et al. 2001; Wang et al. 2004; Chau et al. 2005-a and 2005-b; Ma et al. 2005) are based on integrating (1) 3D models of constructed structures, construction equipments, and site temporary facilities; and (2) schedule plan of construction activities. The integration between project's 3D model and the construction schedule is facilitated by bi-directional links that connect each construction activity with its related structure element, resources, and temporary facilities. This integration results in an informative animation of the 3D representation of construction site activities and resources that help planners in detecting any operational of safety violations. This 3D animation enables construction planners to better understand site management process and dynamically assign site space to construction tasks and facilities considering construction schedule and space availability.

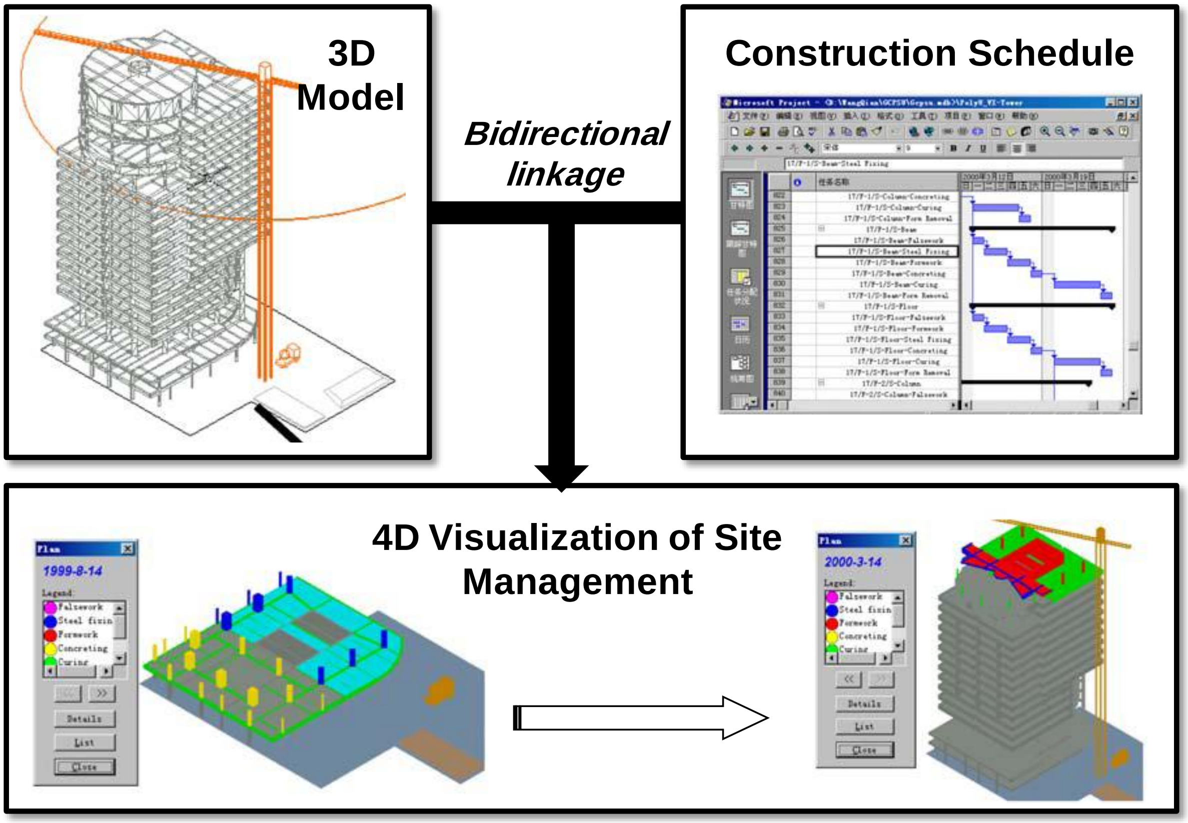


Figure 2.2 4D Visualization Application in Site layout Management and Planning (Wang et al. 2004)

Some of existing 4D visualization models of site layout planning provide various decision support capabilities to help construction planners in taking site layout decisions. Zhang et al. (2001) imbedded in their model a site knowledge management system (SKMS) that utilizes expert systems and artificial neural networks to analyze input information and planner's layout decisions. SKMS uses and updates layout knowledge and rules to check the consistency of planner's decision and propose alternative options based on previous stored expertise. Other models of 4D site visualization comprehend different capabilities such as: (1) dynamic automated calculation of resources that reflects any changes occur in the 3D model (Wang et al. 2004); (2) data warehousing to store, organize and analyze planner's layout decision of previous projects (Chau et al. 2005-a and 2005-b); and (3) providing 3D templates of various components of constructed building as well as site facilities and equipments (Ma et al. 2005). Despite the benefits of 4D site visualization models, they don't provide the sufficient means of optimizing site layout decision and quantifying the impacts of these decisions on various planning objectives such as safety, cost, or security.

2.3 Material Procurement Planning

Material procurement planning is an integral parcel in any construction management that has a significant impact on project productivity and cost (O'Brien and Plotnick 1999). Planning the procurement of construction material involves specifying suppliers, quantities, and dates of materials deliveries considering activities demand and site conditions. Unnecessary early deliveries result in congested construction sites, excessive handling, and lockup of contractor's capital in material inventory. On the other hand, late deliveries increase the criticality of the project and produce activities delay that may lead to contractor's penalties. The following subsections present a summarized literature review of construction material procurement that is organized in three sections: (1) various costs that are impacted by the decisions of material procurement; and (2) existing material inventory systems that model the dynamics of material storage and its replenishment mechanisms.

2.3.1 Material Procurement Costs

Decisions of material procurement have a direct impact on the following main costs (Magad and Amos 1995; Pooler and Pooler 1997; Neale et al. 2006; Polat et al. 2007; Jung et al. 2007):

- ***Purchase Cost***: it is the direct cost of material acquisition to the contractor. Purchase cost involves fixed and variables components. Fixed cost involves the bare cost rate of the material that doesn't change with the order quantity, while the variable component represent the administrative costs of placing the order that decreases as larger quantities of the material are ordered.
- ***Delivery Cost***: it is the expenses of transporting the material from the supplier to the construction site. Similar to purchase cost, delivery cost rate decreases as larger quantities of materials are ordered because of the greater utilization of trucks capacity. Accordingly, it is optimal, in terms of purchase and delivery costs, to order a material quantity in fewer deliveries with larger sizes than more deliveries with smaller sizes.
- ***Handling Cost***: it is the monetary value of crews handling time to move the material from its on-site storage to the construction activity areas. Handling cost is significantly affected by procurement decisions and site layout. Material handling cost can be eliminated if small quantities are delivered directly from the suppliers to the activities locations without the need to have on-site storage. Furthermore, handling cost can be minimized by designing the site layout in the way that locates onsite material storage area as close as possible to its fabrication and/or construction activities areas.
- ***Financing Cost***: or opportunity cost is the return that could have been achieved if the money that is locked up in the on-site material inventory is invested elsewhere. Procurement decisions and material type critically impact the financing cost as frequent small material deliveries eliminates onsite material inventory while costly and expensive resources (e.g. rebar or equipments) generates more financing costs than cheaper resources (e.g. bulk materials such as sand, cement, and soil).

- ***Carrying Cost***: it includes any expenses, other than the financing cost, that occurs because of holding material inventories such as management, taxes, insurance, storage, spoilage, and shrinkage. Although these are traditional cost items associated with material inventory, it relatively constitutes a small portion of the total procurement cost (Neale et al. 2006)
- ***Stock-out Cost***: is any cost to the contractor that occurs due to the shortage of material when needed, which comprehends project delay penalties and labor waiting costs. The material-related delay of critical construction activities or those with short float time results in a delay for the whole project, which may cause costly penalties as stated in liquidated damages section of the project contract. Despite its significance, stock-out cost is the most challenging cost to compute because of its dependency on other complex factors such as activities relations and their criticality (Jung et al. 2007).

2.3.2 Material Inventory Systems

Material inventory systems (or stock control systems) were developed by researchers and practitioners to help in deciding when and how much to order materials to fulfill project demand. These systems are used to plan and control material procurement and inventory considering various objectives such as minimizing cost, maximizing customer satisfaction, or minimizing waste. As shown in Table 2.1, material inventory systems can be categorized into demand-push and demand-pull systems (Pyke and Cohen 1990; Magad and Amos 1995; Pooler and Pooler 1997; Rushton et al. 2000; SM 2009). Demand-push systems are inventory *planning* systems where procurement orders are scheduled in advance using available estimates of demand and supply rates. Examples of demand-push systems include fixed-order-quantity, fixed-order-period, period patch control, materials requirements planning

(MRP1), and manufacturing resource planning (MRP2). On other hand, demand-pull systems are inventory *reacting* systems where material stock replenishment is triggered in construction real time through the depletion of the inventory. Examples of demand-pull systems include reorder point system and just-in-time (JIT). The following subsections provide a brief description about each of the aforementioned material inventory systems.

Table 2.1 Material Inventory Systems

Attribute	Demand-Push Systems	Demand-Pull Systems
Description	Replenishment system is triggered by interpretation of the expected demand and scheduling of supply to meet that demand	Replenishment system is triggered by the usage or depletion of stock
Objective	Minimize Cost	Minimize Inventory and waste
Complexity	High	Low
Methodology	Resource Allocation	Responsiveness
Types	• Fixed-Order-Quantity System • Fixed-Order-Period System • Period Batch Control • Materials Requirements Planning (MRP1) • Manufacturing Resource Planning (MRP2)	• Reorder Point (ROP) System • Just-In-Time (JIT)

In fixed-order-quantity (FOQ) system, inventory replenishment is accomplished through cyclic orders of fixed quantities (Gourdin 2006). As shown in Figure 2.3, the objective of the fixed-order-quantity system to find the optimal order quantity, or economic order quantity (EOQ), that minimizes procurement costs considering the tradeoff between ordering and inventory costs. If the consumption rate is assumed to be fixed overtime, EOQ can be computed by Harris formula (Harris 1913) shown in Equation 2.1. Material safety stock can be kept all time to provide insurance against material shortage due to unforeseen events such as increases in demand rates. If demand rate is variable over time, the objective is to find the optimal times of n equal orders over a finite time horizon (Daganzo 2005), as shown in Figure 2.3.

$$EOQ = \sqrt{\frac{2UO}{MC}} \tag{2.1}$$

Where, EOQ = economic order quantity; U = annual consumption (units); O = order cost ($/order); M = material cost ($/unit); and C = inventory carrying costs (% in decimal form).

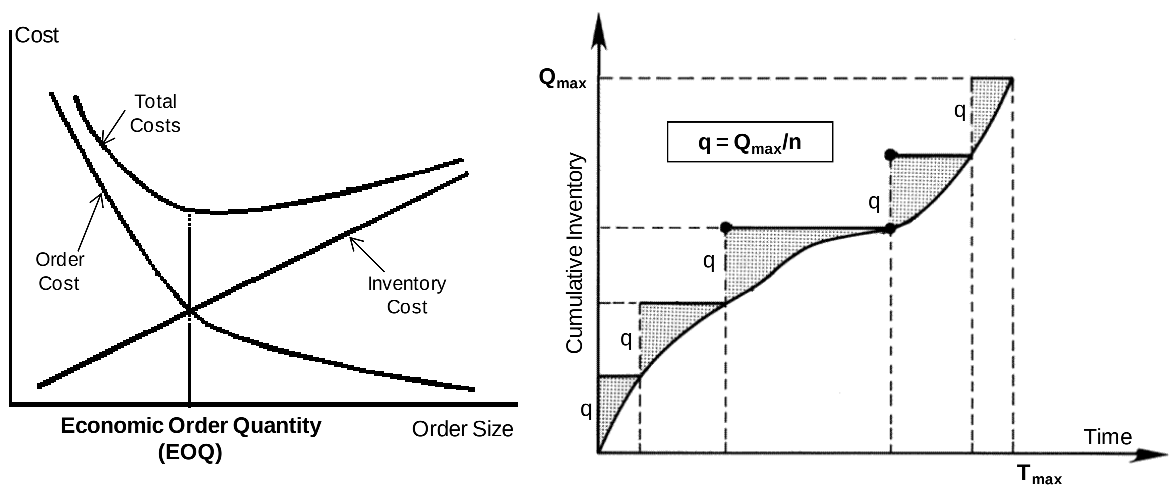


Figure 2.3 Fixed-Order-Quantity System and Economic Order Quantity for Fixed and Variable Demand

Fixed-order-period (FOP) system replenishes material inventory at fixed interval, at which time new orders are placed with different quantities are placed to bring the inventory to a predetermined level (Waller 2003). The objective of this system is to find the optimal ordering period (interval duration) that minimizes material procurement cost considering the tradeoff between ordering and inventory costs. One possible extreme solution is to have very frequent orders with short ordering periods that increase ordering cost but has the lowest inventory cost. On the other extreme, material can be procured in less frequent orders that reduce ordering cost but results in additional inventory costs.

Period patch control (PBC) is a cyclic production planning system that coordinates various stages of production in order to fulfill the demand of the customers and minimize material inventory investment (Benders Riezebos 2002). PBC was introduced in 1930s during the World War II in the manufacturing of fighting airplanes in England. As shown in Figure 2.4, it requires the adoption of a single manufacturing plan (programming) that is repeated in every cycle (Burbidge 1996). The work in the manufacturing plan is divided into a set of successive stages that have the same period of time P. In every cycle, an ordering period is required before the manufacturing plan to accept customers' orders and issue materials procurement requests. This approach of overlapping cycles results in short customers lead times that is best suited to "cellular" manufacturing that involves a set of production groups (cells) that assemble similar parts (Steele and Malhotra 1997). PBC results in the elimination of material stock investments and the double handling of materials because of the cyclic coordination between different production stages. Despite its promising implementation in the manufacturing industry, PBC may not suite construction planning because of the absence of modular design and construction that can be planned in uniform work stages.

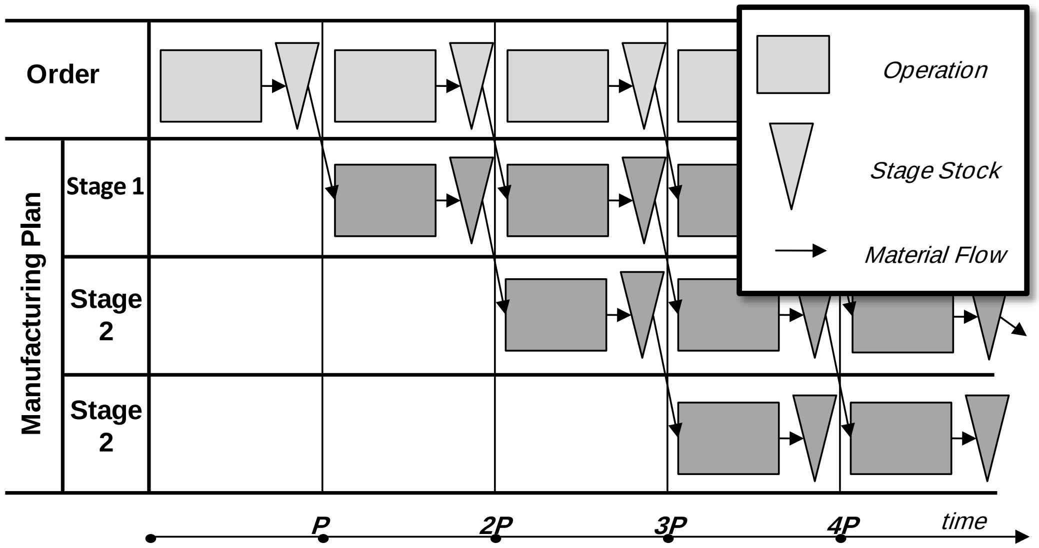


Figure 2.4 Period Patch Control (Benders and Riezebos 2002)

Material Requirements Planning (MRP1) is a computer-based system that coordinates the production schedule with its requirements of materials, parts, assemblies, and subassemblies to support the changing customer demand over time (Pooler and Pooler 1997). As shown in Figure 2.5, MRP1 involves four main processes (Magad and Amos 1995) that are repeated over uniform time intervals: (1) master production scheduling, (2) material requirements planning, (3) capacity requirement planning (CRP), and (4) production control. First, a master production scheduling (MPS) is generated in the beginning to aggregates existing customers orders for each time period in the planning horizon. Second, MRP computes the demand for various materials and/or parts using production Bill of Materials (BOM), existing inventory, and lead times. Accordingly, procurement orders of materials and parts are generated using various EOQ and lot-sizing algorithms (such as Wagner-Whitin method and Silver-Meal heuristic) considering infinite capacity of suppliers as well as manufacturing labors (Neale et al. 2006). Third, capacity requirement planning calculates the start and finish times of different manufacturing operations in the Master Production Schedule (MPS) using different scheduling algorithms such as Critical Path Method (CPM) and resource-constrained scheduling algorithms. Some MRP1 applications facilitate human involvement in this stage to resolve any resources capacity violations in the generated schedule of manufacturing operations. Finally, the production is monitored and controlled to produce inventory and production reports that will be utilized in the following planning horizon. Despite its automation of manufacturing and ordering scheduling, MRP1 is criticized for its medium-term planning focus and the generation of infeasible (resources over-capacity utilization) production schedules (Magad and Amos 1995; Yeung et al. 1998).

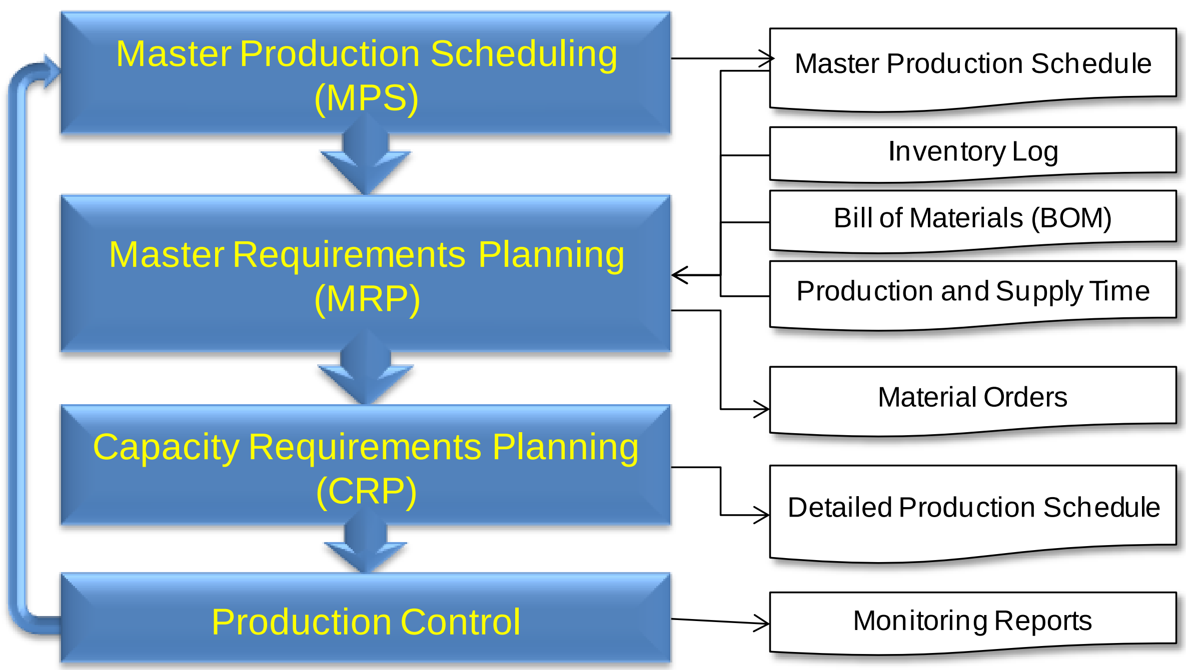


Figure 2.5 Material Requirements Planning (MRP1) System

Manufacturing Resource Planning (MRP2) is an extension of Material Requirement Planning (MRP1) that represents an integration information system that links different manufacturing company operations such as marketing, financing, operations, and purchasing (Sheikh 2002).

While MRP1 is focusing on planning manufacturing operations and materials ordering, MRP2 is about improving productivity through the best utilization of all corporate resources including material, labor, equipment, and money (Rushton et al. 2000). As shown in Figure 2.6, MRP2 utilizes information technology (IT) tools to interconnect between different functions of the corporate such as strategic planning, demand management, sales planning, operations planning, Materials Requirements Planning (MRP1), and shop floor control. MRP2 financially evaluates the whole manufacturing process by converting resources demands (e.g. equipment, material, manpower) into cash outflow and products sale into cash inflow (Pooler and Pooler 1997).

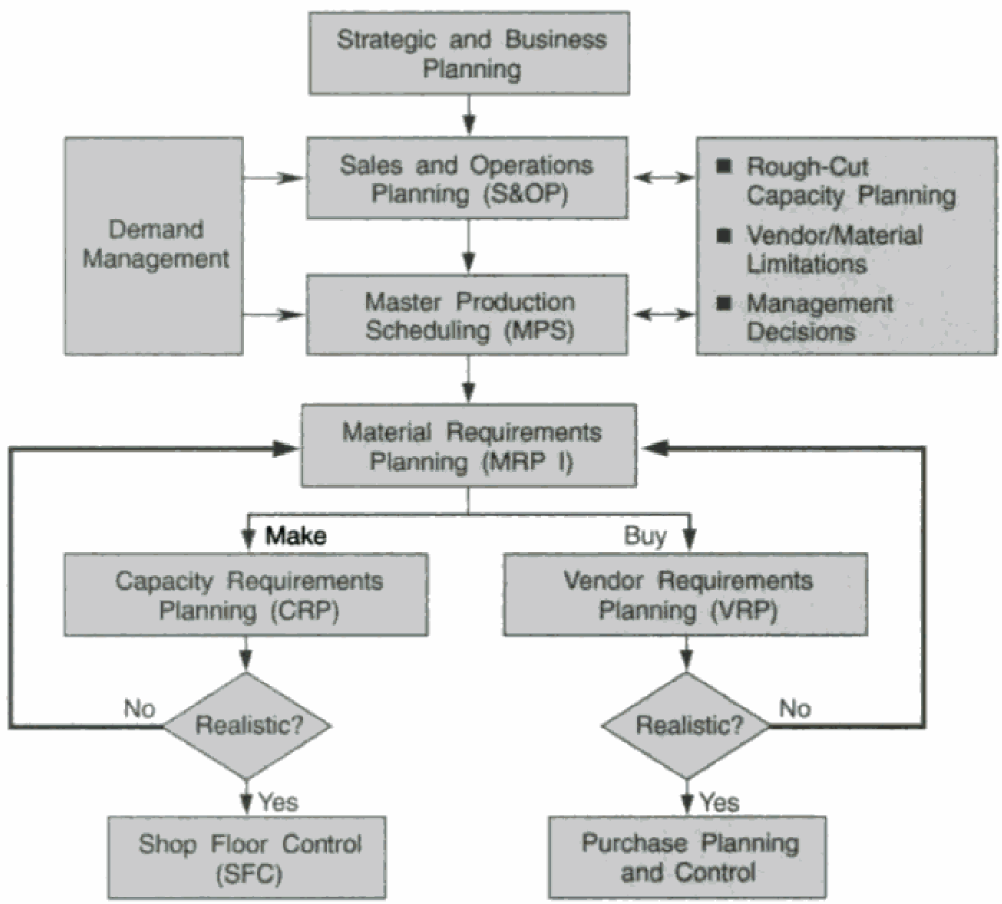


Figure 2.6 Manufacturing Resource Planning (MRP2) System (Sheikh 2002)

Reorder point (ROP) system is a demand-pull approach that replenishes material inventory with fixed order quantities in cycles to keep the inventory between predetermined minimum and maximum levels (Mercado 2007). This system allows the inventory to be consumed until a critical level is reached, which is called the reorder point. As shown in Figure 2.7, ROP system replenishes the inventory using fixed quantity orders with varying time intervals between them. The reorder point is selected to keep the inventory level between a maximum and minimum (safety stock) levels and to eliminate stock-out probability. If the inventory system is considered fixed and deterministic, the reorder point can be calculated using Equation 2.2 using fixed values of demand rate and order lead time (Pooler and Pooler 1997). Otherwise, statistical models or computer simulation can be used to generate the best value for reorder point that considers stochastic demand rate and order lead time (Ness and Stevenson 1983; Jain et al. 2001). There are other inventory systems have been developed with the same analogy of ROP system, such as Min-Max system, and 2 Bin systems (Agarwal 1983).

$$ROP = S + D \times L \tag{2.2}$$

Where, ROP = reorder point; S = Safety stock or inventory minimum level; D = demand rate (units/day); and L = order lead time (days)

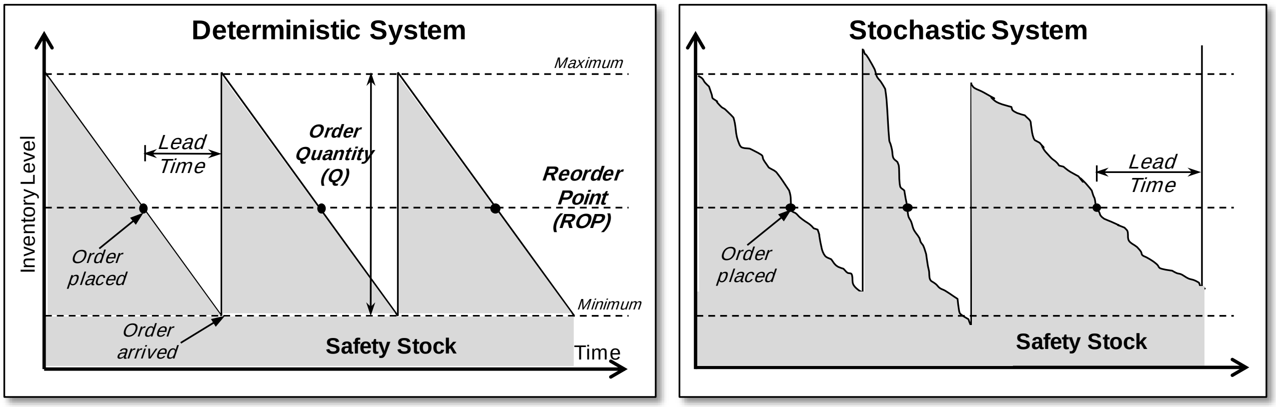


Figure 2.7 Reorder Point System for Deterministic and Stochastic Conditions

Just-In-time (JIT) is a manufacturing approach and philosophy that aims to meet customers demand instantaneously with the perfect quality and no waste (Rushton et al. 2000). JIT originated in Toyota car manufacturing in Japan to delivery high quality products and eliminate all sources of waste that include overproduction, waiting times, material handling, and defects (Pooler and Pooler 1997). JIT is a management philosophy that covers all the functions of the manufacturing process, including: human resources management, total quality management, facilities design, preventive maintenance, and material procurement and purchase. Enhancing relationships with suppliers and reducing order and setup costs are the main approaches of JIT to improve materials procurement (Magad and Amos 1995). First, the relations between the manufacturing process and its suppliers should be improved to reach the level of partnership and cooperation. The main characteristics of suppliers' partnership, in JIT context, are long term relationships, commitment to firm delivery schedules, frequent deliveries, and mutual continuous improvement. Second, JIT aims at reducing ordering and setup cost that would facilitate smaller and frequent material procurement orders. As shown in Figure 2.8, smaller values of economic order quantity (EOQ) can be obtained if ordering and setup costs are cut through the synchronization between suppliers and manufacturers (Waller 2003; Magad and Amos 1995). Smaller values of EOQ result in more frequent material deliveries that is a critical factor of eliminating material inventories and their wastes.

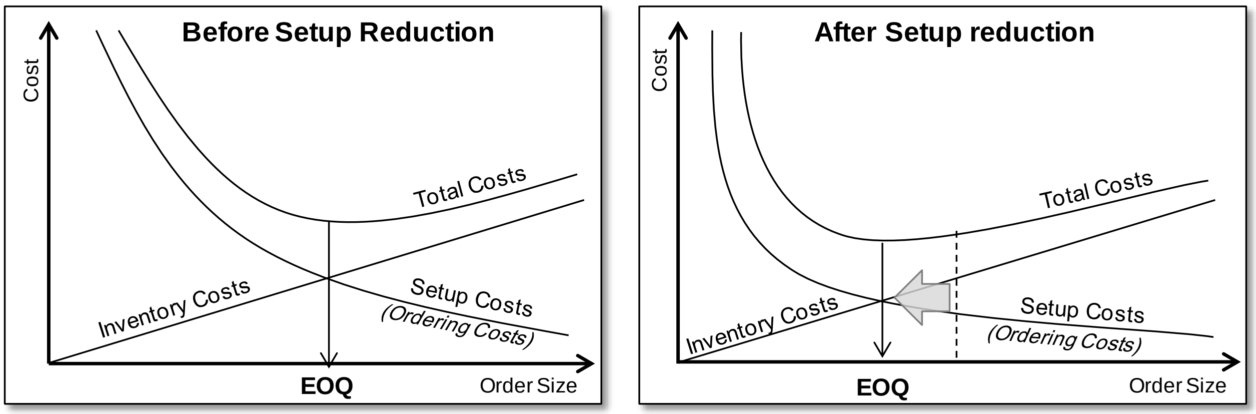


Figure 2.8 JIT Setup Reduction Effect on EOQ (Magad and Amos 1995)

2.4 Construction Material Management

Although construction material management derives its fundamental theories and practices from the manufacturing business, construction industry imposes unique challenges because of its project-oriented focus and dynamically changing environment (Ibn-Homaid 2002). Accordingly, a set of research studies and developments have been developed to help contractors and planners to optimally plan material procurement and storage in construction projects. These research studies and developments can be reviewed in these main groups: (1) investigating the impact of material management practices on construction labor productivity; (2) applying Just-in-time philosophy in construction projects; (3) implementing 4D visualization to manage and control material supply and storage on site; (4) developing decision support systems for economical material supply chains; (5) developing data exchange and integration standards in construction supply chains; and (6) investigating logistics management implementation in construction projects. The following subsections discuss in more details the developments in each of these research areas of construction material procurement and supply.

2.4.1 Material Management Impact on Productivity

Several research studies investigated the impact of material management practices related to material procurement and storage on construction productivity. Thomas et al. (1989) performed a study to quantify the potential benefits of applying effective material management in commercial construction project. This research study compared between two similar construction projects where the first one implemented a systematic material management while the second one did not. In each project, a set of data were collected including productivity rates, materials delivery, onsite storage, and handling. Qualitative and quantitative analyses were performed to indentify the correlation between material management practices and productivity disruptions. This study concluded that the implementation of effective material management in these project resulted in a benefit/cost ratio of 5.7. Thomas et al. (1999) studied the impact of structural steel delivery methods and weather on labor productivity. It was concluded that erecting the steel directly from the truck is effective because of the elimination of off-loading and sorting times onsite. Also, productivity losses due to adverse weather are quantified to be 41% for snow and 32% for cold weather.

Thomas and Sanvido (2000) studied the impact of the relationships between contractors and fabricators on construction productivity. They found that late deliveries, fabrication errors, and unordered deliveries resulted productivity losses that range between 16.6% and 56.8%.

Horman and Thomas (2005) analyzed the impact of material inventory buffers on construction productivity in rebar fabrication and erection activities. They concluded that the optimal inventory level is between 4% and 5.5% (measured as the progress difference between erection and fabrication activities) to maintain high productivity rates and minimize work disruptions. Thomas et al. (2005) developed a set of fundamental principles to enhance site material management. These principles focus on dividing onsite material existence into three zones (exterior storage, staging areas, and interior storage) as well as facilitating efficient communications between project contractors and suppliers.

2.4.2 JIT implementation in Construction

Inspired by its success in the manufacturing industry, researchers investigated the implementation and suitability of Just-in-Time approach in controlling construction material procurement. Akintoye (1995) presented an overview of JIT implementation issues in managing materials inventories of building construction projects. This study highlighted various factors that impact the effectiveness of JIT implementation in building construction projects such as vendors' relationships, design standardization, construction site layout, and staff training and education. Furthermore, benefits of JIT implementation are identified to include communication improvement, inventory reduction, quality improvement, simplification of ordering procedures, and building long-term relationships with suppliers. Bertelsen and Nielsen (1997) investigated the implementation of JIT in the Danish building construction industry, concluding that JIT requires careful planning, daily monitoring, and immediate feedback mechanism.

Pheng and Hui (1999) studied the correlations between JIT principles and site layout planning in a building project. Seven JIT principles were considered in this study: elimination of waste, kanban pull system, uninterrupted work flow, total quality control, employee involvement, supplier relationships, and continuous improvement. The implementation of each of these principles was evaluated in a building construction project focusing on its impact on site layout planning. The researchers suggested performing more research on quantitatively measuring the performance of JIT and to study the contribution of reduced inventory costs on project's cash flow. Polat and Arditi (2005) presented a comparison between JIT and just-in-case (JIC) approaches in terms of procurement costs in Turkey as a representation of developing countries. They developed a simulation model to mimic the supply of rebar using JIT and JIC approaches in order to estimate the total cost of procurement, which includes purchasing, financing, handling, storage, delivery, shortage, and waiting costs. Using actual data from a case study, the simulation analysis found that procurement costs of JIT approach were 4.4% higher than those of JIC. Accordingly, the researchers concluded that although JIT removes inventory and its associated costs, it also sacrifices inventory benefits especially in uncertain markets like the case of developing countries.

2.4.3 4D Visualization of Material Site Storage

Subsomboon and Christodoulou (2003) developed a material-status monitoring system, named FIAPP that controls material procurement processes in 4D and 3D environments in integrations with other managerial tasks such as bidding and constructability analysis. FIAPP system is design to help building contractors to: (1) standardize and automate the generation of the bill of materials; (2) assist in defined work scope and bidding packages for project suppliers and vendors; (3) facilitate material procurement monitory using color-coding 4D animations showing real-time status of material deliveries. The proposed system provides a collaboration environment for planners, architectures, engineers, and vendors using 3D computer models and database-driven systems.

2.4.4 Optimization Models of Construction Material Management

Optimization models and decision support tools were developed to help contractors and planners in optimally planning material procurement and storage on construction sites. Tserng et al. (2006) developed an integrated inventory cost information system (IICIS) for planning construction material production and supply in order to optimize inventory costs of both contractors and suppliers. IICIS is designed to generate optimal supply and production plans of rebar manufacturing using the concept of constraint programming in order to minimize integrated inventory costs for the whole supply chain. The developed system didn't consider other sources of procurement costs such as delivery and shortage costs.

Another study was carried by Jung et al. (2007) to develop a statistical algorithm in order to generate optimal procurement plans of raw material and time lags between fabrication and erection of construction rebar activities. The developed algorithm utilizes Monte Carlo Simulation to obtain optimal inventory level and estimate total inventory costs of rebar raw materials and fabricated products. Supplying rebar raw material (inbound process) is modeled as a pull system while the rebar fabrication delivery (outbound process) is modeled as a push system. Accordingly, the decision variables are the order quantity and reorder level of raw materials as well as the time lag between the fabrication and the delivery of the assembled products to the construction site. The inventory cost is estimated in this algorithm as the summation of delivery and stock-out cost. The proposed algorithm was tested in a real-life case study and generated an optimal solution with 25% savings in inventory costs compared to the actual production plan.

Jang et al. (2007) developed an floor-level construction material layout planning model that utilizes Genetic Algorithms (GA) to generate optimal material layout plans to minimize weighted handling distances between material storage and work areas. Locations of activities work areas and the sizes of the material storage areas are predefined by the planner. Material storage areas for every activity are placed considering available spaces and their pair-wise weights based on the importance and needs frequency of each material. Furthermore, the developed model quantifies materials handling considering vertical and horizontal distance between storage and work areas as well as the locations of vertical handling hoists.

In another study, Polat and Arditi (2007) developed a simulation-based decision support system that produces optimal procurement strategy of construction rebar through the consideration of three main factors: buffer size, scheduling strategy, and lot size. Buffer size represents the time lag between the start of an activity and the finish of its predecessors, which can take three values of large, medium, and small. Planning strategy is the way that uncertainty and variability are handled in the supply and fabrication of rebar, which has three options: optimistic, neutral, and pessimistic. Lot size is the size of rebar orders that can be either “small” (Just-in-Time situation) or “large” (Just-in-Case situation). Accordingly, the developed model helps contractors select the best economical solution from the 18 available options of all possible combinations of buffer size, scheduling strategy, and lot size. Computer simulation is used to model rebar supply chain that includes procurement, unloading, fabrication, and assembly processes. The output of the model is the best economical solution that minimizes total inventory cost, which comprises purchase, financing, handling, storage, delivery, waiting, and shortage costs.

2.4.5 Data Exchange Standards

During the last two decades, the Architectural, Engineering and Construction (AEC) industry has witnessed the development of data exchange standards that models project products and processes. Danso-Amoako et al. (2004) studied the suitability of two of these standards, International Foundation Classes (IFC) and CIMSteel Integration Standards (CIS/2), to model and represent the procurement and scheduling processes within the steel fabrication and erection supply chain. This study formulated a representation for construction steel supply chain that depends on the fabricator as the main actor who orders steel raw materials from the suppliers and supply finished steel elements to the contractors in order to be erected onsite. It was concluded in this study that IFC standard is generally more adequate than CIS/2 to allow process modeling and representation of material procurement and drawings approval. For example, IFC has provisions such as *IfcCMDocPackage* within the *IfcConstructionMgmtDomain* that handles steel-specific documents. Furthermore, temporal data such as delivery dates and critical activities can be represented using *ifcScheduleTimeControl* entity in IFC. Accordingly, the study provides a set of recommendations and approaches to expand the structure of both IFC and CIS/2 to efficiently represent steel fabrication and erection.

2.4.6 Construction Logistics Planning

Logistics can be defined as the efficient transfer of goods from the source of supply to the points of consumption in a cost-effective way while achieving acceptable level of customer satisfaction (Rushton et al. 2000). A series of research studies have been performed to investigate the application of logistics in the construction industry. Caron et al. (1998) developed a stochastic model to plan the delivery of construction material to building sites considering the variability of the delivery dates and construction productivity rate. The developed model integrates the procurement and construction phases in the aggregate level in early planning stages. The output of this model is not a detailed procurement plan but rather a set of requirements that the procurement plan should meet to ensure the continuity of the construction project. Accordingly, the model generates the best "required availability" curve ahead of the construction progress curve that the detailed procurement plan should fulfill. To facilitate the integration between procurement and construction phases, cumulative construction progress and required availability curves are measured in equivalent standard man-hours of construction that convert physical work of material transformation into its corresponding man-hours.

Agapiou et al. (1998) presented a conceptual model of construction logistics to manage the flow of materials from the suppliers to the installation onsite. This study highlighted the need to manage and control material logistics in early project phases with the emphasize on effective interfaces between project parties (designers, contractors, fabricators, and suppliers), exchange of information, and extension of company's processes outside of its organizational boundaries based on partnership agreements. The output of this logistics model is an accurate procurement plans keyed to detailed delivery dates, site locations, and storage arrangements. Other studies (Silva and Cardoso 1999; Salagnac and Yacine 1999; Guffond and Leconte 2000) presented general guidelines in implementing logistics management in construction industry that include: (1) utilization of efficient information systems and mechanisms for information exchange between major actors of the logistics process; (2) development of supply plans in the long, medium, and short (weekly) terms; and (3) generating and updating dynamic site layout plans that considers material flow and handling alternatives.

Wegelius-Lehtonen 2001 presented a performance measurement framework for construction logistics that classifies its metrics based on their focus and purpose. Based on the focus, performance metrics are used in two levels: general contractor level and suppliers' level. On the other hand, performance metrics can be classified based on its purpose as improvement and monitoring. The former type is used in the start and end of project developments to find logistics improvement area, while the later is used during the project for continues performance monitoring. Another study by Jang et al. (2003) surveyed the satisfaction of project managers for construction logistics including five main factors: personnel, material flow, schedule adherence, contractor's organization, and information flow. Based on the survey, a set of multiple regression analyses were performed to correlate between the overall satisfaction of managers and their feedback on each of the survey factors as well as the correlation among these factors. The survey showed the significance of all these factors on project manager's satisfaction of construction logistics. Furthermore, survey responses highlighted the need for additional improvement in technologies and software of construction logistics.

Sobotka (2000) proposed a simulation modeling approach to optimize reengineering of internal logistics systems in construction companies and evaluate improvement alternatives of material and information flows. The simulation approach is designed to evaluate two possible structures of construction logistics systems while considering different values of their controlling design parameter such as quantities and frequency of material orders. The first logistics structure, DSSL_3, involves delivering material orders from the suppliers to the construction sites as well as the central storage area of the construction company based on individual needs of the sites and material supply strategy for the whole company. The second logistics structure, DSSL_6, enforces all material orders to be sent to the central storage area and then distributed to the construction sites. Accordingly, reengineering of the logistics system is optimized to select the optimal of the two logistics structures and the values of their controlling parameters in order to minimize logistics costs (ordering and carrying costs).

2.5 Construction Security Regulations

Few federal regulations have been produced to establish security requirements and arrangements during the construction of critical infrastructure projects (Branch and Baker 2007). The National Industrial Security Program (NISP) was established, by Presidential Executive Order number 12829 (PEO 1993), to enforce security regulations on private industries in order to safeguard federal classified information that is released to contractors and subcontractors in federal projects. The objective of the NISP is establish single, integrated, and cohesive system for safeguarding classified information held by private industry to: (1) enhance the quality of security procedures especially those related to physical security and personnel clearance; (2) eliminate duplicated or unnecessary requirements imposed by different agencies involved in one single project; and (3) minimize costs of securing sensitive information held by private industry contractors. Based on the NISP, the Department of Defense produced National Industrial Security Program Operating Manual (NISPOM) to provide general requirements and procedures for contractors about securing any of their facilities (offices, labs, etc) where federal sensitive information is being accessed and processed (DOD 2006).

Federal Aviation Administration (FAA) established a set of guidelines and regulations in a number of advisory circulars and reports, such as "*Aviation Security – Airports"* (FAA 1972) and "*Recommended Security Guidelines for Airport Planning, Design, and Construction"* (FAA 2001). These documents propose a set of countermeasures and procedures that contractors should consider during the construction or expansion of airports, such as: (1) the early involvement of airport security personnel in the planning and engineering phase airport construction and renovation projects; (2) frequent update of construction site and airport operation zones in order to consider the mutual impacts between construction and aviation activities; (3) using personal identification systems for contractor's labors to limit their access to critical portions of the airport; and (4) planning access points and routing of contractor's vehicles in order to coordinate it movements with aircrafts and minimize any conflicts with aviation operations. Beside these federal regulations, airports establish additional construction security regulations that are incorporated in bidding documents issued to contractors (Spence 1990).

The Department of State (DOS) produced a number of security manuals to assure that adequate steps have been taken to safeguard sensitive information which is released to contractors and subcontractors during the construction of U.S. overseas diplomatic facilities

(FAM 1994; FAM 1997; FAM 2002). These manuals were established to: (1) assure that all new construction or renovation projects of overseas facilities comply with DOS construction security standards; (2) define the responsibilities of site security manager assigned by DOS to monitor security countermeasure implementation during the construction phase; (3) approve construction security plans proposed by project contractor and site security manager to secure Sensitive Compartmented Information Facilities (SCIF) where sensitive information are being processed (DCID 2002); and (4) apply security clearance investigations on construction firms and contractor personnel who have access to Sensitive Compartmented Information (SCI).

2.6 Physical Security Engineering and Design

Physical security engineering is the design of protective system for critical resources and targets against attack, sabotage, and theft using a set of security countermeasures (Hay 2001). It deals with the development of detailed engineering plans for the implementation of security countermeasures using different analysis techniques such as risk assessment, cost-benefit analysis, and space planning (Demkin 2004). Security countermeasures are implemented in zones and layers that collectively deter, detect, delay, and detain any intruders or attackers breaching for protected assets. The following subsections describe in more details previous research studies and developments in the domain of physical security engineering.

Grassie et al. (1990) proposed a Structured Countermeasure Selection Process (SCSP) in order to help security system designers to select the economical implementation of different security countermeasures considering existing threats and limited budgets. The developed system is designed to help decision maker to select best countermeasure options of security system main components: physical barriers, detection equipments, communication systems, security personnel, and security procedures and policies. SCSP involves six main steps: (1) identify assets; (2) determine criticality of assets; (3) determine threats; (4) determine modes of attacks; (5) determine vulnerability; and (6) determine required protection. Security countermeasures in the proposed process are divided into three groups: asset-specific, facility-specific, and site-specific countermeasures. Security designer selects required countermeasures considering the overall cost of the system that is the cost summation of all countermeasures. The cost effectiveness of each countermeasure is calculated considering different lifecycle costs of installation, operation, and maintenance.

Comparative Layout Analysis for Secure Fences (CLASP) is a mathematical model that was developed to assist security designers and practitioners to evaluate and compare a set of possible alternatives for security fences in terms of performance and cost (Tarr 1992; Tarr 1994; Tarr and Peaty 1995). Security fences are evaluated by CLASP using six performance metrics: detection, intervention, worst intervention, false alarms, capital cost, and equivalent annual cost. Intervention calculation is the core part of CLASP that calculates the chance of detaining an attacker given a specific set of barriers, alarm systems, response force, and site layout. CLASP calculates intervention probability based on the three security functions of detecting the attackers by the intrusion detection systems; delay them by fence barriers; and detaining them by the response force. The model relates these three “D” functions in a mathematical formulation based on the assertion that the intervention can only happen if the attacker is detected and the response time is less than the delay time. CLASP is designed to consider different types of attack styles (cutting, ladder, rope, etc) as well as the existence of different segments design in the same security fence.

Bilbao (1992) developed a risk analysis model for security designers to evaluate different types of risks utilizing fault tree analysis and fuzzy set operations. First, major risks against an asset are identified such as burglary and theft. Second, each major risk is decomposed into its simple risks that represent occurrence prerequisites such as window penetration or fence jumping. Simple risks are connected to their major risks using fault trees representation through AND-gates and OR-gates. Similarly, simple risks can be broken down into its sub-risks until basic criminal actions are reached with measurable occurrence probability (P) and consequences (T). Third, fuzzy sets are used to represent occurrence probabilities and the consequences of the simple risks in the modeled fault tree. Fourth, occurrence probability and consequence of each risk in a specific level of the fault tree are calculated based on its simple risks and the type of relation (AND-gate or OR-gate) using fuzzy set operations. These fuzzy set operations are performed until the P and T parameters are obtained for the major risks in the system. Finally, the severity of each major risks R is obtained as a fuzzy set using P and T parameters calculated in the previous step. The severity of each major risk is compared to five predefined fuzzy patterns of risks (from very low, low, medium, high, and very high) in order to determine the representing pattern using a fuzzy set parameter called Euclidian distance.

In another study, Strutt et al. (1995) developed a security risk assessment methodology to analyze the adequacy and compatibility of security countermeasures and quantitatively asses the probability of successful completion of predefined attacker's mission. The proposed methodology involves three main phases: (1) data collection, (2) protection analysis, and (3) summarizing and reporting. First, all available data are collected including possible threats, attack objectives or targets, attack frequency, attacker competence, and consequences for each threat/objective combination. Second, protection analysis is performed to calculate the probability of successful attacks for each threat/objective combination. The physical representation of the system in this analysis involves a set of barriers around attack objectives and paths that intruders can take to reach their objectives and/or escape. The probability of successful attacks is calculated in the analysis phase considering barriers negotiation times, intrusion an escape paths, and reaction time for response forces. Finally, the output of the previous phase is used to perform cost/benefit analysis to compare between the costs and risk mitigation for different options of the security system.

Cost and Performance Analysis (CPA) model is a decision support system for security practitioners, which integrates activity-based cost estimation and performance-based analysis of physical security systems (Hicks et al. 1998; Hicks et al. 1999). CPA consists of two major modules: cost analysis tool for security system (CATSS) and performance module (PERFORM). CATSS is built around another tool called ACEIT (Automated Cost Estimating Integrated Tools) that supports lifecycle cost analysis considering installation, operation, maintenance, and demolition costs. PERFORM is a post-analysis module that integrates the results of security computer applications such as ASSESS (Analytic System and Software for evaluating Safeguards and Security) and JTS (Joint Tactical Simulation). The performance of a physical security system is quantified using a probabilistic metric that depends on two main factors: (1) probability of interruption (PI) and (2) probability of neutralization (PN) for each attacker/response force combination. Probability of interruption

(PI) is a function of the detection probabilities and delay times on different paths in the system as well as the required time for the response force to interrupt the intruder. Based on the results of CATSS and PERFORM modules, cost/benefit analysis is performs in a way that correlates costs with probabilistic performance metrics in order facilitate operational and strategic decision of the security system designer.

2.7 Multi-Objective Optimization

Multi-objective (or multi-criteria) optimization is the process of optimizing a group of conflicting objectives subject to a set of constraints (Goldberg 1989). In multi-objective optimization, there is no single optimal solution, as optimizing one objective results in the degradation of solution's quality in other objectives. Instead, a group of optimal solution exists that consider different tradeoff between the conflicting objectives (Ehrgott 2005). As shown in Figure 2.9, these tradeoff solutions are called Pareto-optimal set that dominate the rest of possible solution by better performances in all considered objectives. Multi-objective optimization problems can be solved using different approaches and tools (Deb 2001), such as: (1) weighted sum method; (2) Є-constraint method; (3) weighted metric method; (4) Benson's method; (5) value function method; (6) goal programming; and (7) Evolutionary Algorithms.

Evolutionary Algorithms (GA) became favorable over other multi-objective approaches because of its population-based search and efficiency in discontinuous and non-differential problems (Fonseca and Fleming 1993). Several multi-objective Evolutionary Algorithms (MOEA) tools have been developed (Deb 2001) that utilize the concepts of solutions non-domination and elitism, such as: (1) Strength Pareto Evolutionary Algorithm (SPEA); (2)

Pareto Archived Evolutionary Strategy (PAES); (3) non-dominated sorting genetic algorithm (NSGA); and (4) elitist non-dominated sorting genetic algorithm (NSGA-II). A number of research studies compared between these MOEA tools and reported the promising performance of NSGA-II over the other tools (Deb et al. 2001; Zitzler et al. 2001, Hiroyasu 2006). NSGA-II was noticed to generate better optimal tradeoff solutions with broader spread of the Pareto front and better distribution of solutions.

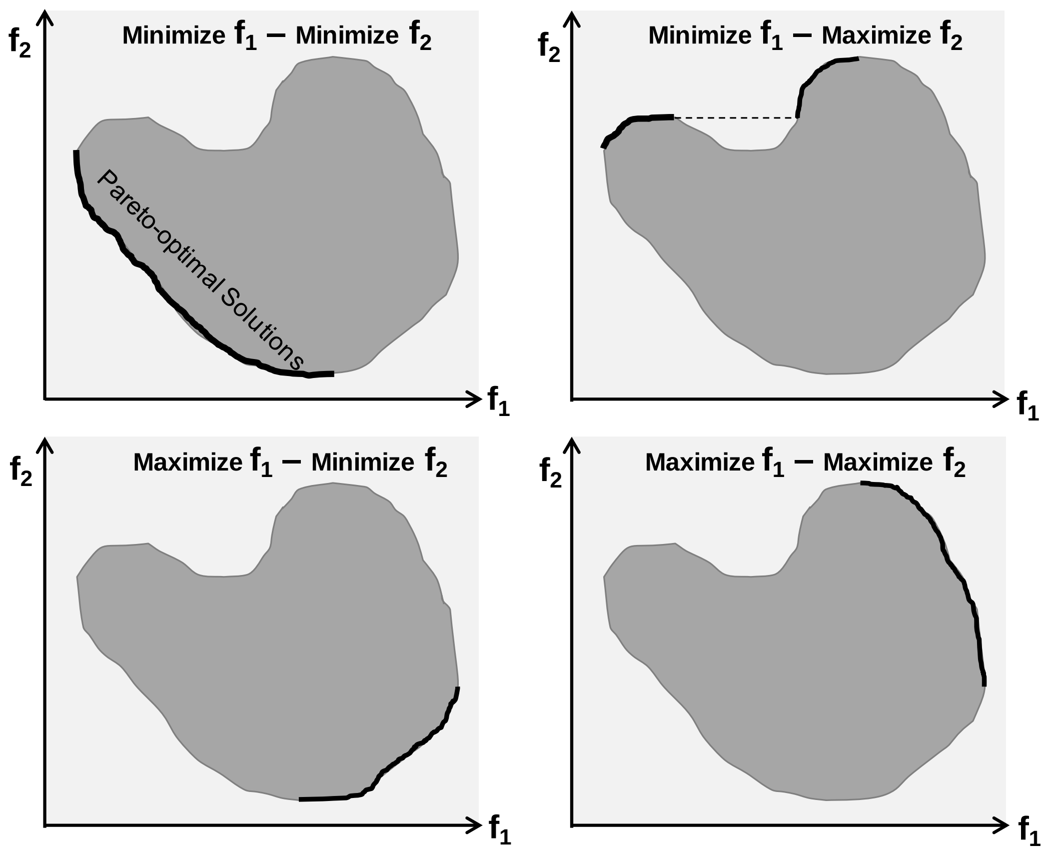


Figure 2.9 Pareto-Optimal Tradeoff Solutions (Deb 2001)

2.8 Summary

This chapter reviewed relevant literature and research developments in the areas of dynamic site layout planning, material procurement planning, construction material management, construction security regulations, physical security engineering, and multi-objective optimization. Current models of dynamic site layout planning adopt the same chronological approach that may result in non-optimal or infeasible solutions. Furthermore, current models of DSLP and material procurement don't consider the mutual impacts between supply and layout decisions. Few construction security regulations were established by Federal Aviation Administration, Department of State, and Department of Defense. These regulations don't consider the unique environment of the construction projects and the impact of site layout planning on the security level of critical infrastructure construction sites. Reviewed literature in the area of multi-objective optimization revealed the robustness of elitist non-dominated sorting genetic algorithm (NSGA-II) in efficiently and effectively generating Pareto-optimal solution that consider different tradeoffs between the contradicting. In the following chapters, the performance of this optimization tool will be evaluated in optimizing construction logistics planning on the construction sites of critical infrastructure projects.

CHAPTER 3
DYNAMIC SITE LAYOUT PLANNING MODELS

3.1 Introduction

The main objective of this chapter is to develop robust global optimization models of dynamic site layout planning that are capable of minimizing layout costs. The proposed models are designed to overcome the limitations of existing models that result in non-optimal or infeasible solutions. The proposed models generate optimal layout decisions in every construction stage considering the future impact on the layout quality of subsequent stages. The development of these models involves four main steps: (1) formulating the problem of dynamic site layout planning and the modeling assumptions related to space and time representation of construction site and facilities; (2) the implementation of the first DSLP model using Genetic Algorithms (DSLP-GA); (3) the implementation of the second DSLP model using Approximate Dynamic Programming (DSLP-ADP); and (4) performance evaluation and comparison of the developed models of dynamic site layout planning. The following sections of this chapter describe in details each of these development steps.

3.2 Problem Formulation and Assumptions

The construction site in the proposed DSLP models is represented as a 2D rectangular space that is reorganized and updated in distinct successive points of time during the project duration. Schedule milestones can be considered as a timetable to reorganize the layout of the construction site, where these times represent remarkable release or new demand of site space. The space within the construction site is decomposed into a grid of locations, where the number of locations depends on the grid pitch specified by the planner. The DSLP framework considers these grid locations to position and/or relocate temporary facilities dynamically over the project duration.

Construction site facilities are represented using 2D rectangular shapes and categorized into three types: fixed, stationary, and moveable facilities:

- *Fixed Facilities* are those with predetermined fixed positions on site such as the constructed building and site access. Planners do not need to select the locations of these facilities as their positions and dimensions are predetermined and can be extracted from the construction drawings.

- *Stationary Facilities* are temporary facilities that planners need to determine their positions only once such as tower cranes and batch plants. These facilities are not allowed to be repositioned on site in later project stages due to the significant time, cost, and/or effort required to relocate them.

- *Moveable Facilities* are temporary construction facilities that can be relocated at the start of any of the identified project stages. Examples of moveable facilities include site offices, testing laboratories, storage areas, fabrication areas, and rest areas. A moveable facility can be relocated in cases where there is newly freed space that is better than its currently occupied spot, or if other new facilities have a greater need for its current location. The ability to modify the locations of moveable facilities in various project stages can improve the efficiency of the overall site layout; however this repositioning requires an additional relocation cost.

3.3 Model 1: Genetic Algorithms (DSLP-GA)

The first proposed DSLP model is an evolutionary-based optimization model that is capable of globally optimizing dynamic site layout planning. This optimization model is implemented using Genetic Algorithms (Deb et al. 2001) that mimics the metaphor of natural biological evolution by using a set of genetic operators (selection, crossover and mutation) to search for global optimum solutions of complex problems. The following sections describe the main three components of the proposed evolutionary-based optimization model (DSLP-GA): decision variables, layout constraints, and optimization objective.

3.3.1 Decision Variables

DSLP-GA model generates optimal dynamic site layout that involves the decisions on the locations and orientations of the temporary facilities in every construction stage. As shown in Figure 3.1, the model identifies the *position-able* facilities, in each stage, that include: 1) all moveable facilities that continue on site from the previous stage; and 2) all new moveable and stationary facilities that are used for the first time in this stage. For example, facilities F2 and F3 in Figure 2 are identified as position-able facilities in the second stage because F2 is a movable facility that is used in the previous stage while F3 is a new stationary facility that is used for the first time in the second stage. It has to be noted that moveable facilities are identified as position-able facilities in all stages where they exist while stationary facilities are identified as position-able facilities only in the first stage where they are being used. Accordingly, the decision variables are the location and orientation (either 0º or 90º) of each position-able facility in every construction stage. Each facility is positioned in one of the grid positions that are defined based on the grid pitch specified by the planner.

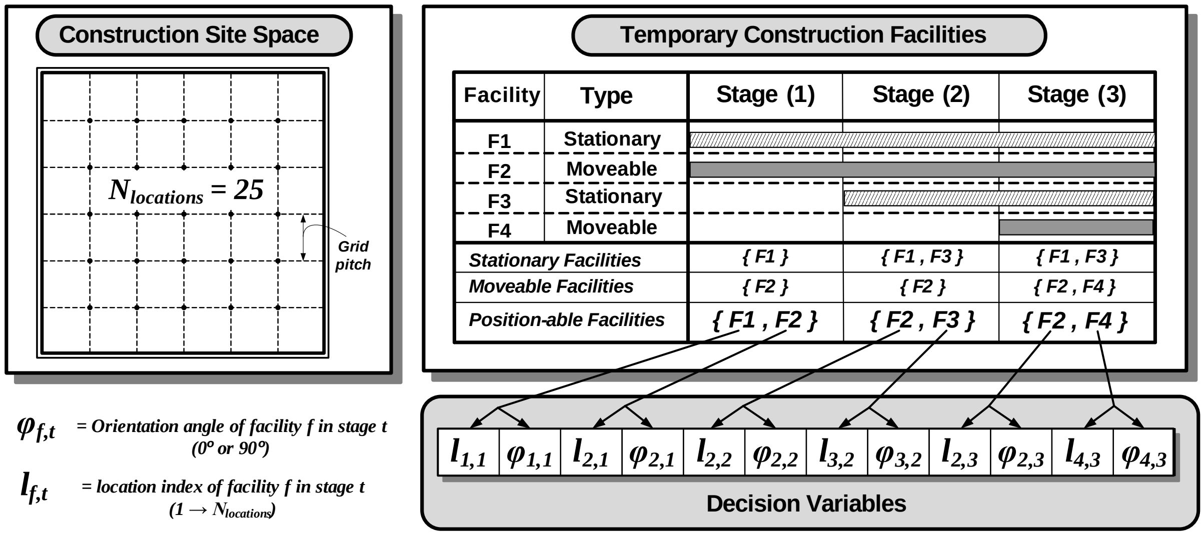


Figure 3.1 Decision Variables and GA String Representation

The number of decision variables in the model is affected by the number of planner-defined construction stages. For each of these stages, the model is designed to represent the positioning of each temporary facility with two decision variables (i.e., location and orientation). Accordingly, the total number of decision variables in the model is equal to the summation of the number of decision variables in all the planner-specified stages. The quality of site layout planning can be enhanced by increasing the number of these stages as it provides more frequent updates of the site layout needs. This increase in the number of stages, however, creates a larger number of decision variables which requires more computational time and cost. This tradeoff between the quality of the site layout solution and the computational costs needs also to be considered by planners when they specify the number of stages. Planners can specify the start of these stages to coincide with schedule milestones, which represent the finish and start of major tasks and accordingly the release of and demand for significant site space.

3.3.2 Optimization Objectives

The present module considers dynamic site layout planning as an optimization problem with the objective function of minimizing the total site layout cost. As shown in Equation 3.1, the objective function comprises two cost components: travel cost (*TC*) and relocation cost (*RC*). For each construction stage, these two types of costs are calculated and their sum is globally minimized. First, the travel cost (*TC*) is calculated between any pair of construction facilities *i* and *j* (fixed, moveable, or stationary facilities) that exist in the same stage based on the Euclidian distances (D_{ij}^{t}) and the traveling cost rates (TCR_{ij}^{t}) between them in the corresponding stage t (Equation 3.2). Second, the relocation cost (*RC*) is calculated using Equations 2.3 and 2.4 for each moveable facility in every construction stage (except the first stage) if any one of the following two conditions were encountered: (1) the orientation (φ_{m}^{t}) of the facility is changed while maintaining its location in the previous stage; or (2) moving the facility from its previous location to a different one regardless of its new orientation. For the case of relocating the moveable facility by moving it, the relocation cost has a fixed component (FRC_m), and a variable component ($VRC_m D_{mm}^{t(t-1)}$) that depends on the relocation distance.

Minimize total site layout cost = Minimize {TC + RC} (3.1)

$$TC = \sum_{t=1}^{T} \sum_{i=1}^{F_t - 1} \sum_{j=i+1}^{F_t} TCR_{ij}^{t} D_{ij}^{t} \tag{3.2}$$

$$RC = \sum_{t=2}^{T} \sum_{m=1}^{NMF_t} RC_{m}^{t(t-1)} \tag{3.3}$$

$$RC_{m}^{t(t-1)} = E_m \times \begin{cases} 0 & \varphi_{m}^{t} = \varphi_{m}^{t-1} \quad AND \quad D_{mm}^{t(t-1)} = 0 \\ \left(FRC_m + VRC_m D_{mm}^{t(t-1)}\right) & Otherwise \end{cases} \tag{3.4}$$

Where,

TC = travel cost;

RC = relocation cost;

T = number of construction stages;

F_t = number of construction facilities (fixed, moveable, and stationary) in stage t;

NMF_t = number of moveable facilities in stage t;

TCR_{ij}^{t} = traveling cost rate ($/meter) between facilities i and j in construction stage t;

D_{ij}^{t} = Euclidian distance (m) between facilities i and j in stage t;

$RC_i^{t(t-1)}$ = relocation cost ($) of temporary facility i in stage t from its previous position in stage t-1;

E_m = existence coefficient equals to 1 if the moveable facility m exists in previous stage t-1, and 0 otherwise;

FRC_m = fixed relocation cost ($) for relocating moveable facility m;

VRC_m = variable relocation cost ($/meter) for relocating moveable temporary facility m one meter Euclidian distance;

φ_m^t, φ_m^{t-1} = orientation angles of moveable facility m in stage t and t-1;

$D_{mm}^{t(t-1)}$ = Euclidian distance between the locations of moveable facility m in stages t and t-1; and

3.3.3 Layout Constraints

The positioning of any temporary facility should consider a set of geometric constraints that can be categorized in two main groups: default and operational constraints. *Default Constraints* include boundary and overlap constraints that are imposed automatically by the present framework on the layout decision of any position-able facility. Boundary constraints are imposed to guarantee that all temporary facilities are positioned within the site boundaries. As shown in Figure 3.2, boundary constraints are satisfied for each facility (F_i) when the two conditions in Equation 3.5 are satisfied simultaneously. Overlap constraints are imposed to prevent any overlapping between any pair of facilities (i,j) by satisfying at least one of the two conditions in Equation 3.6.

$$\left|X_{site} - x_i\right| \le \left(LX_{site} - \left(Lx_i \cos\varphi_i + Ly_i \sin\varphi_i\right)\right)/2; \text{ And}$$

$$\left|Y_{site} - y_i\right| \le \left(LY_{site} - \left(Ly_i \cos\varphi_i + Lx_i \sin\varphi_i\right)\right)/2 \tag{3.5}$$

$$\left|x_i - x_j\right| \ge \left(Lx_i \cos\varphi_i + Ly_i \sin\varphi_i\right)/2 + \left(Lx_j \cos\varphi_j + Ly_j \sin\varphi_j\right)/2; \text{ Or}$$

$$\left|y_i - y_j\right| \ge \left(Ly_i \cos\varphi_i + Lx_i \sin\varphi_i\right)/2 + \left(Ly_j \cos\varphi_j + Lx_j \sin\varphi_j\right)/2 \tag{3.6}$$

Where,

x_i, y_i = the orthogonal coordinates of the center of facility i;

X_{site}, Y_{site} = the orthogonal coordinates of the center of the construction site;

Lx_i, Ly_i = the defined width and length of facility i with zero orientation angle (φ_i);

LX_{site}, LY_{site} = the defined width and length of the construction site; and

φ_i, φ_j = orientation angle of facilities i and j, respectively.

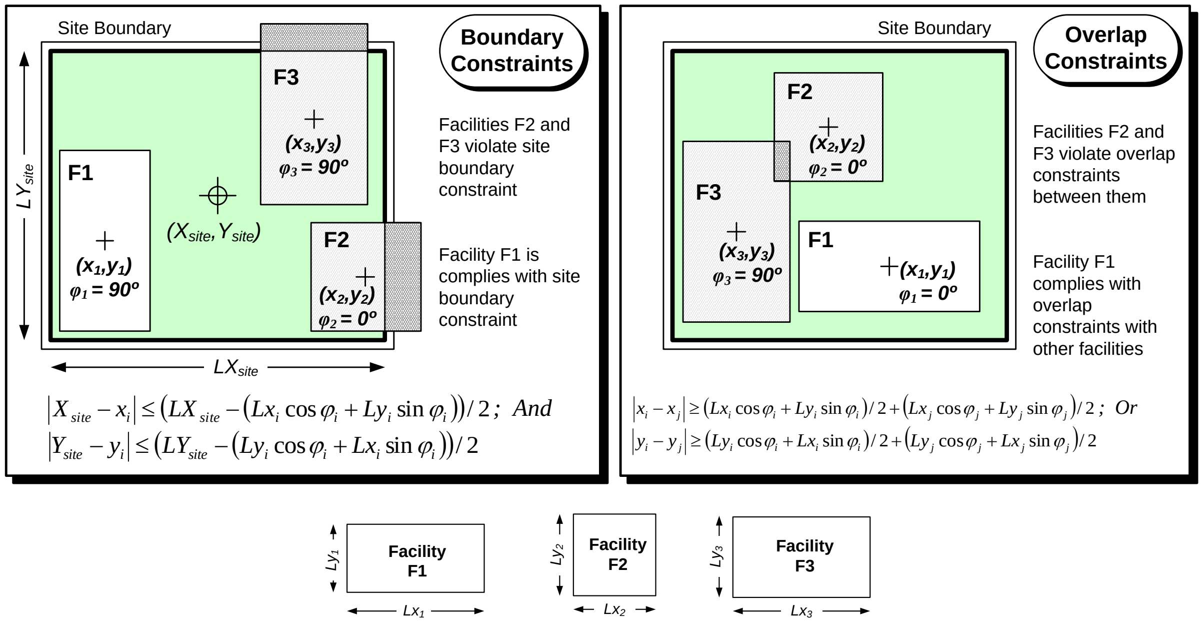


Figure 3.2 Default Site Layout Constraints

Operational Constraints are imposed on facilities layout to comply with constructability, safety, or any planning requirements on site. As shown in Figure 3.3, operational constraints include *minimum/maximum distance* and *exclusion/inclusion zone* constraints. *Minimum distance* constraint can be used to provide safety buffer distances around constructed buildings to minimize the hazards of falling objects. Compliance with the *minimum distance* constraint between facilities *i* and *j* requires satisfying at least one of conditions stated in Equation 3.7. On the other hand, the distance between tower crane and its supply points should not exceed the reach of the crane jib, which can be represented by a *maximum distance* constraint for this constructability requirement. *Maximum distance* constraint between facilities i and j is satisfied when both of the two conditions in Equation 3.8 are satisfied. *Exclusion/Inclusion zone* Constraints are imposed to limit the presence of a construction facility outside or inside a specified zone on site. As shown in Figure 3.3, an exclusion zone can be placed around the access gate to restrict the positioning of any construction facility in this access area by applying an *exclusion-zone* constraint, which is complied with if any of the two conditions in Equation 3.9 is satisfied. On the other hand, *inclusion zone* constraint is used to restrict the positioning of a facility to be within a specified inclusion zone by satisfying both of the two conditions in Equation 3.10 (see Figure 3.3).

$$\left|x_i - x_j\right| \geq \left(Lx_i \cos\varphi_i + Ly_i \sin\varphi_i\right)/2 + \left(Lx_j \cos\varphi_j + Ly_j \sin\varphi_j\right)/2 + D_{ij}^{\min}; \text{ Or}$$

$$\left|y_i - y_j\right| \geq \left(Ly_i \cos\varphi_i + Lx_i \sin\varphi_i\right)/2 + \left(Ly_j \cos\varphi_j + Lx_j \sin\varphi_j\right)/2 + D_{ij}^{\min} \quad (3.7)$$

$$\left|x_i - x_j\right| \leq \left(Lx_i \cos\varphi_i + Ly_i \sin\varphi_i\right)/2 + \left(Lx_j \cos\varphi_j + Ly_j \sin\varphi_j\right)/2 + D_{ij}^{\max}; \text{ and}$$

$$\left|y_i - y_j\right| \leq \left(Ly_i \cos\varphi_i + Lx_i \sin\varphi_i\right)/2 + \left(Ly_j \cos\varphi_j + Lx_j \sin\varphi_j\right)/2 + D_{ij}^{\max} \quad (3.8)$$

$$\left|x_i - \left(X_z^U + X_z^L\right)/2\right| \geq \left(Lx_i \cos\varphi_i + Ly_i \sin\varphi_i\right)/2 + \left(X_z^U - X_z^L\right)/2; \text{ Or}$$

$$\left|y_i - \left(Y_z^U + Y_z^L\right)/2\right| \geq \left(Ly_i \cos\varphi_i + Lx_i \sin\varphi_i\right)/2 + \left(Y_z^U - Y_z^L\right)/2 \quad (3.9)$$

$$\left|x_i - \left(X_z^U + X_z^L\right)/2\right| \leq \left(X_z^U - X_z^L\right)/2 - \left(Lx_i \cos\varphi_i + Ly_i \sin\varphi_i\right)/2; \text{ and}$$

$$\left|y_i - \left(Y_z^U + Y_z^L\right)/2\right| \leq \left(Y_z^U - Y_z^L\right)/2 - \left(Ly_i \cos\varphi_i + Lx_i \sin\varphi_i\right)/2 \quad (3.10)$$

Where

$D_{ij}^{\min}$, $D_{ij}^{\max}$ = the minimum/maximum distance allowed between facilities (*i*,*j*).

X_z^L, X_z^U = the coordinates of the lower and upper bounds of the zone parallel to *Y* axis; and

Y_z^L, Y_z^U = the coordinates of the lower and upper bounds of the zone *z* parallel to X axis.

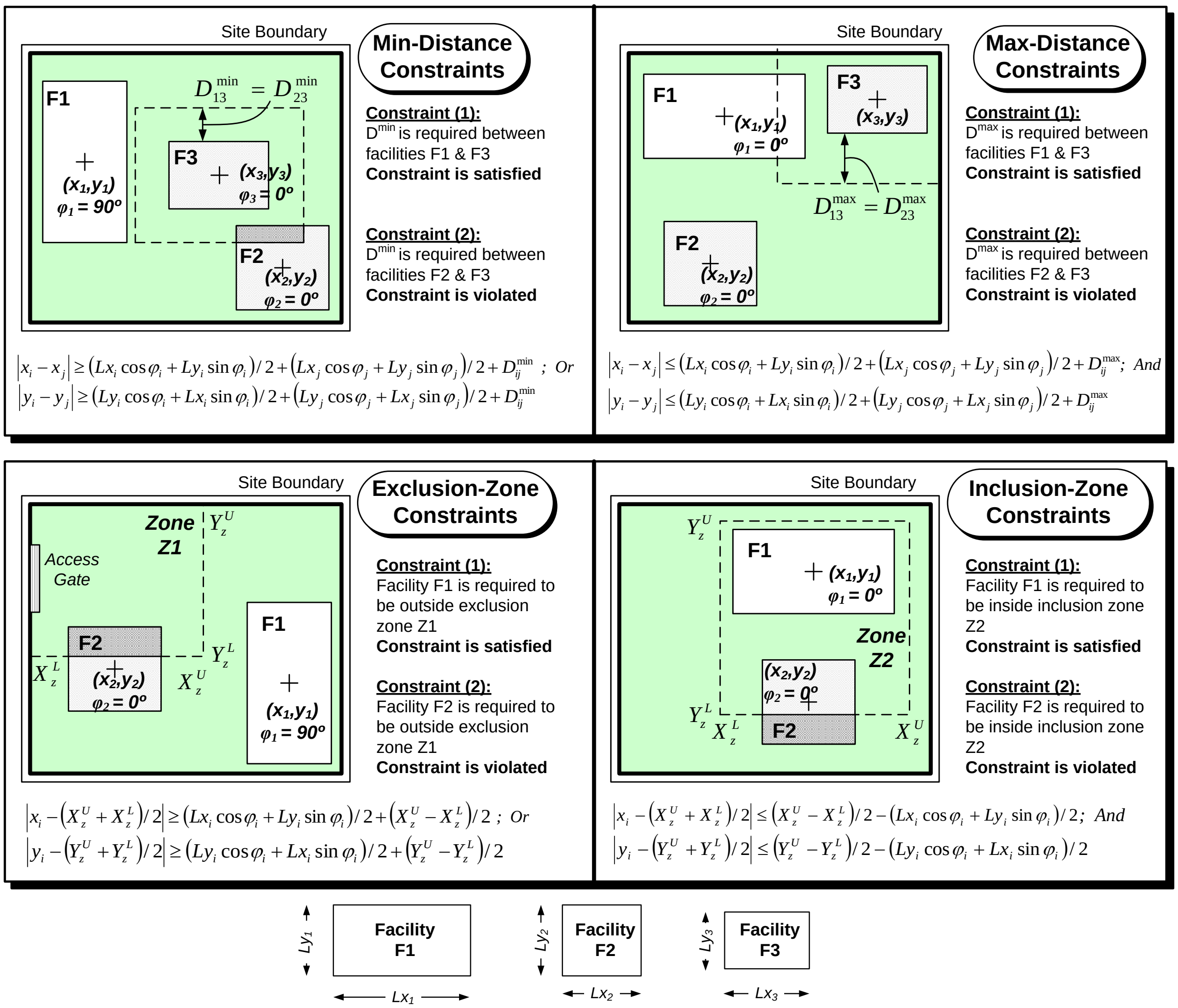


Figure 3.3 Operational Site Layout Constraints

3.4 Model 2: Approximate Dynamic Programming (DSLP-ADP)

The second proposed DSLP model utilizes Approximate Dynamic Programming (ADP) to model the present complex and multidimensional site layout planning problem that requires the optimization of site layout decisions for multiple facilities in successive stages. Approximate Dynamic Programming (ADP) offers a powerful methodology to analyze complex and multidimensional dynamic problems that are computationally hard to solve using traditional Dynamic Programming (Powell et al 2005). The following subsections describe the six main components of the proposed DSLP-ADP model: decision epochs, state vector, transition function, contribution function, optimality equation, and ADP algorithm.

3.4.1 Decision Epochs

Modeling a complex problem using dynamic programming requires breaking it down into a set of simpler and easier sub-problems (decision epochs) that are solved sequentially to generate the optimal solution for the larger problem (Zayed 2002). As shown in Figure 3.4, the decision epochs are used in the present model to represent the positioning decisions of every position-able (i.e., moveable or new stationary facility) in every construction stage. For example, the present model identifies facilities F2 and F3 (see Figure 2) as position-able facilities in the first stage because F2 is a new stationary facility that was not positioned before, while F3 is a moveable facility. Similarly in the second and third stages, facilities F3 and F4 are identified as position-able facilities because both are moveable facilities. In each decision epoch d, an action (Xd) is taken to determine the values of the two decision variables (the location and orientation) of the corresponding facility in the current stage. As shown in Figure 3.4, a chain of decision epochs can be constructed for the site layout planning problem, where each decision epoch refers to the positioning decision of a specific position-able facility in each construction stage. Accordingly, the number of decision epochs in the present model is calculated as shown in Equation 3.11. For the example shown in Figure 3.4, the site layout planning model is composed of 6 decision epochs that represent two decision epochs for the two position-able facilities in each of the three construction stages.

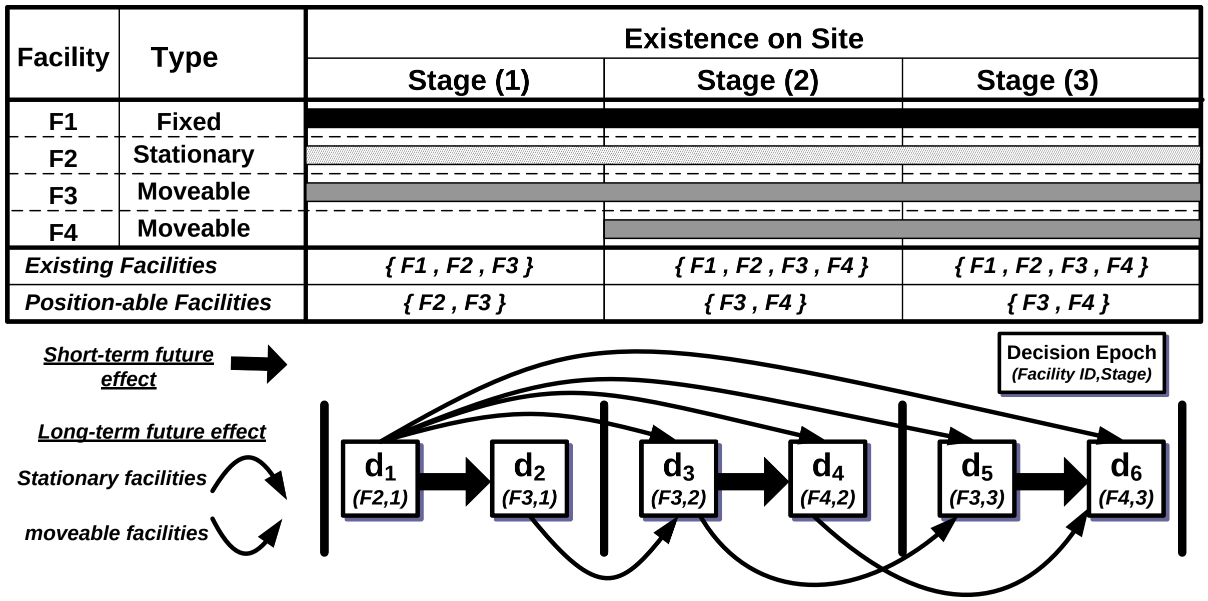


Figure 3.4 Decision Epochs in DSLP-ADP Model

$$D = \sum_{t=1}^{T} NPF_t \tag{3.11}$$

Where

D = number of decision epochs;

T = number of construction stages; and

NPF_t = number of position-able facilities in construction stage t.

The present dynamic site layout planning problem can be classified as a non-serial dynamic programming (Bertelé and Brioschi 1972), because each decision epoch can have a short-term and/or long-term effect on future decisions epochs, as shown in Figure 3.4. The “short-term effect” is used to describe the impact of positioning a facility on the subsequent decisions in the same stage, such as the effect of decision epoch d_3 on d_4 in Figure 3.4. The “long-term effect” is used to represent the impact of positioning either a stationary or moveable facility in the current stage on the subsequent positioning decisions in future stages. As shown in Figure 3.4, the positioning of stationary facilities (e.g. d_1) affects the positioning decisions of all other facilities in future stages (d_3, d_4, d_5, and d_6). Similarly, the positioning of moveable facilities (e.g. d_3) has long-term effect on positioning the same facility in future stages (e.g. d_5) as shown in Figure 3.4. The present model keeps track of all preceding epochs that have either a short or long-term effects on epoch d, and represents this information using a vector named *Preceding Decision Epochs* (PDE_d). For example, decision epoch d_6 (i.e., positioning facility *F4* in the third stage) is affected both in the short and long-terms by preceding epochs d_1, d_4, and d_5, and accordingly its PDE_6 includes these three epochs as shown in Figure 3.5.

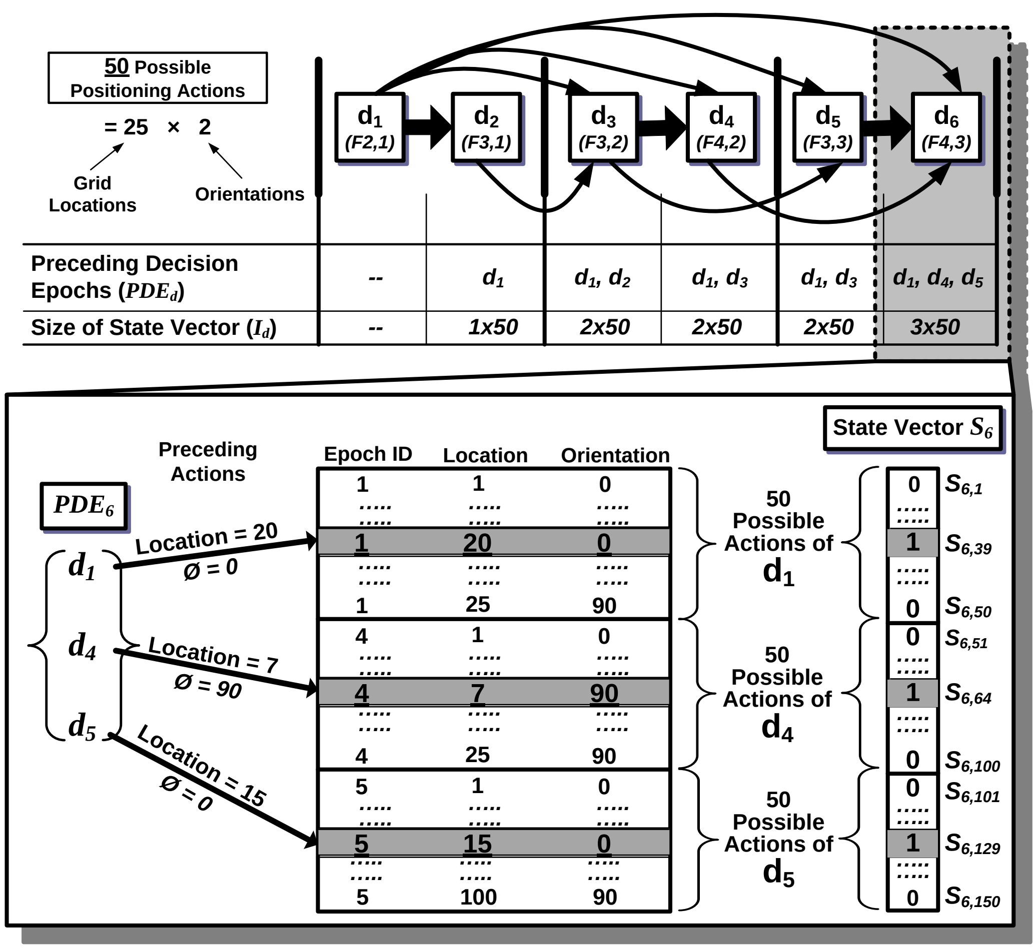


Figure 3.5 State Vector Representation

3.4.2 State Vector

State vector (S_d) is the minimal description of system history at decision epoch d that is crucial to compute the possible reward or cost of the current decision (Denardo 2003). In the present model, the description of system historey at decision epoch d is needed to keep track of the free and occupied spaces on site and to compute the travel and relocation costs. State vector (S_d) is represented by a vector of binary values that captures the decisions made (i.e., locations and orientations) in each of the *Preceding Decision Epochs* (PDE_d). The size (I_d) of the state vector (S_d) is calculated by multiplying the number of preceding decision epochs by the number of possible positioning decisions, as shown in Figure 3.5. For example, state vector S_6 in Figure 3.5 is a vector of 150 binary values that are used to refer to the 50 possible actions (25 locations with 2 possible orientations) of each of the three PDE's (d_1, d_4, and d_5). Each element of the state vector S_6 is assigned a binary value of either 1 if the corresponding action was chosen or 0 otherwise. It should be noted that there are only three elements in the 150 binary elements in S_6 that will have a binary value of 1 (i.e., $S_{6,39}$, $S_{6,64}$, and $S_{6,129}$) because only one action can be selected for each of the three *PDE's*.

3.4.3 Transition Function

The transition function in the present model represents the dynamics in the system and how the states of the future decision epochs are affected as a result of the taken actions in early epochs (Powell 2007). For each decision epoch (d), the transition function ($S_{d'}(X_d)$) is used to update the state vectors of the affected future epochs (d') based on the taken action (X_d) as shown in Equation 3.12. For the example shown in Figure 3.5, taking an action in decision epoch d_1 requires updating the state vectors of subsequent decision epochs d_2, d_3, d_4, d_5, and

d_6 because d_1 exists in their *PDEs*. The state vector of each of these decision epochs is updated by making the value of the corresponding state vector element equal to 1.

$$S_{d'}(X_d) = S_{d'} + \ell_{d'X_d}, \qquad \forall d' \text{ where } d \in PDE_{d'} \tag{3.12}$$

Where,

d' = any future decision epoch that is affected by decision epoch d, where $d \in PDE_{d'}$;

$S_{d'}$ = state vector of future decision epoch d'; and

$\ell_{d'X_d}$ = a vector with the same size as $S_{d'}$ that consists of zero values except for the element that refers to the decision value of X_d for epoch d.

3.4.4 Contribution Function

The contribution function ($C_d(S_d, X_d)$) is used in the present model as a "local" measure of the optimization objective at each decision epoch d (Denardo 2003) by returning the current site layout costs incurred as a result of taking action X_d based on the current state S_d, as shown in Equations 3.13, 3.14 and 3.15. The cost of positioning a temporary facility depends on whether it is a moveable or a stationary facility. The positioning cost of each moveable facility ($C_d(S_d, X_d)_{moveable}$) includes the travel cost (TC_d), relocation cost (RC_d), and constraint-violation cost (CVC_d), as shown in Equation 3.13. The travel cost is calculated for all resources that are required to travel between the positioned moveable facility and 1) all temporary facilities that have already been positioned in the current stage; 2) all fixed facilities that exist in the current stage; and 3) all stationary facilities *continuing* from previous stages. On the other hand, the positioning cost of each stationary facility ($C_d(S_d, X_d)_{stationary}$) includes only the travel cost (TC_d) and constraint-violation cost (CVC_d), as shown in Equation 3.15. It should be noted that the travel cost of positioning a stationary facility comprise its travel cost with every fixed and continuing stationary facilities in current and future stages where this facility exists (i.e., stages t_1 to t_2).

$$C_d(S_d, X_d)_{moveable} = TC_d + RC_d + CVC_d$$

$$= \left(\sum_{i=1}^{P_d} TCR_{di}^t D_{di}^t + \sum_{j=1}^{NFF_t} TCR_{dj}^t D_{dj}^t + \sum_{k=1}^{NCF_t} TCR_{dk}^t D_{dk}^t \right) + RC_d + \left(NCV_d^t \mathrm{P} \right) \tag{3.13}$$

$$RC_d = E_d \times \begin{cases} 0 & \varphi_{\bar{d}} = \varphi_d \quad AND \quad D_{d\bar{d}} = 0 \\ \left(FRC_d + VRC_d D_{d\bar{d}} \right) & Otherwise \end{cases} \tag{3.14}$$

$$C_d(S_d, X_d)_{stationary} = TC_d + CVC_d$$

$$= \left(\sum_{i=1}^{P_d} TCR_{di}^t D_{di}^t + \sum_{y=t_1}^{y=t_2} \left(\sum_{j=1}^{NFF_y} TCR_{dj}^y D_{dj}^y + \sum_{k=1}^{NCF_y} TCR_{dk}^y D_{dk}^y \right) \right) + \left(\sum_{y=t_1}^{y=t_2} \left(NCV_d^y \mathrm{P} \right) \right) \tag{3.15}$$

Where,

t = construction stage where the decision epoch d is taken;

TC_d = travel cost of resources traveling to and from the temporary facility positioned by epoch d;

RC_d = relocation cost of moveable facility positioned by epoch d after it was positioned in the previous stage; and

CVC_d = constraint-violation cost of the facility positioned by epoch d;

P_d = number of already positioned facilities before decision epoch d in stage t;

TCR_{di}^{t} = the travel cost rate (\$/m) between the facility positioned by action X_d and already positioned facility *i* in the same stage *t*;

D_{di}^{t} = the travel distance between facility positioned by action X_d and facility *i* in the same stage *t*;

E_d = existence coefficient equals to 1 if the moveable facility positioned at epoch *d* exists in previous stage *t-1*, and 0 otherwise;

φ_d = orientation angle of moveable facility positioned by action X_d;

FRC_d = fixed relocation cost (\$) of moveable facility positioned at epoch *d*;

VRC_d = variable relocation cost (\$/meter) of moveable facility positioned at epoch *d*;

NFF_t = number of fixed facilities at stage *t*;

NCF_t = number of continuing stationary facilities in stage *t* positioned at previous stages;

$\bar{d}$ = decision epoch that refers to the same moveable facility positioned by *d* but in previous stage *t-1*;

$D_{d\bar{d}}$ = the relocation distance of facility positioned by decision epoch *d* after it was positioned in previous stage by epoch $\bar{d}$;

t_1 and t_2 = the first and last construction stages of the existence of stationary facility positioned by decision epoch *d*;

NCV_d^t = number of constraint-violations in stage t caused by taking action X_d; and

P = constraint-violation penalty factor.

3.4.5 Optimality Equation

The optimality equation is a recursive function that is designed to minimize the current cost $C_d(S_d, X_d)$ of taking action X_d in decision epoch *d* as well as its future cost $V_{d'}\left(S_{d'}(X_d)\right)$ in all the affected subsequent epochs (*d'*), as shown in Equation 3.16. For example, the model selects the optimal action at decision epoch d_3 (see Figure 3) that minimizes: 1) the current cost calculated by the contribution function $C_d(S_d, X_d)$ based on the actions taken in d_1 and d_2 which are stored in state vector S_3; and 2) the future costs $V_{d'}\left(S_{d'}(X_d)\right)$ in epochs d_4 and d_5. Because future costs cannot be calculated exactly with the available information, they are approximated using vectors of linear regression factors analogous to state vectors (Bertsimas and Demir 2002). Accordingly, the future layout cost in the exact optimality equation (Equation 3.16) is approximated as shown in Equation 3.17. This approximation is accomplished by multiplying the updated state vector ($S_{d'}(X_d)$) by its regression factors vector ($\bar{\theta}_{d'}$) for each of the affected future epochs (*d'*), as shown in Equation 8. It should be noted that the accuracy of this approximation in ADP improves iteratively by updating the values of these regression factors vector ($\bar{\theta}_{d'}$) over a number of specified iterations (*N*). This iterative procedure for improving the approximation is described in more details in the following ADP algorithm section.

Exact Optimality Equation:

$$V_d(S_d) = \min_{X_d}\left\{C_d(S_d, X_d) + \sum_{d'} V_{d'}\left(S_{d'}(X_d)\right)\right\} \tag{3.16}$$

Approximated Optimality Equation:

$$\hat{v}_d = \min_{X_d}\left\{C_d(S_d, X_d) + \sum_{d'}\left(S_{d'}(X_d)\cdot\bar{\theta}_{d'}\right)\right\} \tag{3.17}$$

Where,

$V_d(S_d)$ = the minimum layout cost of being in state S_d at decision epoch d;

$C_d(S_d, X_d)$ = the current layout cost (contribution function) of taking action X_d at decision epoch d based on state S_d (see Equation 3.13);

d' = is any decision epoch that is affected by the current decision (i.e., $d \in PDE_{d'}$);

$S_{d'}(X_d)$ = the updated state of d' as a result of taking action X_d (see Equation 3.12);

$V_{d'}(S_{d'}(X_d))$ = the future layout cost at decision epoch d' with the updated state $S_{d'}(X_d)$;

$\hat{v}_d$ = the approximated minimum layout cost of being in state S_d at decision epoch d; and

$\bar{\theta}_{d'}$ = vector of linear-regression factors, of size $I_{d'}$, used to calculate the approximate future layout cost at decision epoch d';

3.4.6 Implementation Algorithm

The Approximate Dynamic programming (ADP) in the present model is an iterative forward path algorithm that depends on approximating the optimality equation and updating this approximation iteratively. ADP algorithm steps forward through the chain of decision epochs, where decisions are made successively starting from the first epoch (Si et al 2004). The detailed procedure of the present ADP algorithm is explained in the following sections and shown in Figure 3.6.

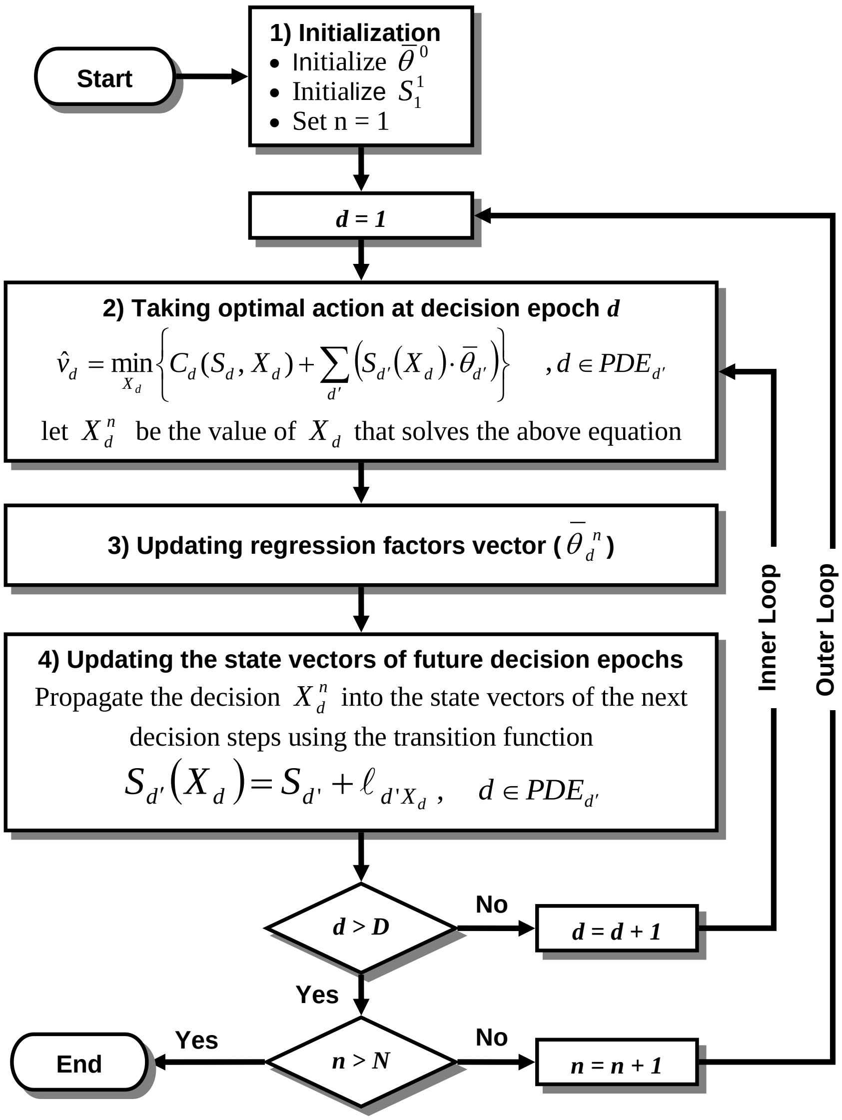


Figure 3.6 ADP Algorithm for Dynamic Site Layout Planning

1. **Initialization**

The algorithm starts by initializing the values of regression factors and the initial state of the construction site layout. First, regression factors are initialized with zero values. Second, the initial state of the construction site layout is provided by identifying the layout of all temporary facilities positioned before running the model. This enables the model to be used at any time during the construction phase to dynamically plan the site layout of the remaining construction work based on the current layout at the analysis time.

2. **Taking optimal action at decision epoch *d***

At decision epoch *d*, the model applies the approximated optimality equation (Equation 3.17) to search for the optimal action (X_d) to position the corresponding facility using the updated regression factors ($\bar{\theta}_d$). The model then records the optimal action X_d^n and its resulting approximate layout cost $\hat{v}_d^n$.

3. **Updating regression factors vector ($\bar{\theta}_d$)**

The calculated approximate layout cost $\hat{v}_d^n$ resulting from action (X_d^n) at decision epoch *d* is then used to update the previous estimate of the regression factors vector ($\bar{\theta}_d$) using the concept of gradient stochastic smoothing (Powell 2007).

4. **Updating the states of future decision epochs**

The model utilizes the transition function (Equation 3.12) to update the state vectors of all future decision epochs that are affected by taking action (X_d^n) at decision epoch *d*.

Steps 2 through 4 are repeated for each decision epoch (d = 1 to D) in a forward path algorithm, as shown in the internal loop in Figure 3.6. This forward path algorithm is repeated over N iterations (see the external loop in Figure 3.6) to improve the approximation accuracy of the algorithm by updating the values of the regression factors ($\bar{\theta}_d$). After the completion of the external loop, the algorithm extracts the global optimal actions $\left(X_d^*\right)_{d=1}^D$ that produce the minimum total site layout cost.

3.5 Performance Evaluation

The performance of the developed models (DSLP-GA and DSLP-ADP) of dynamic site layout planning is evaluated using: (1) an application example from the literature to compare the performance of the developed models with one of the existing DSLP models; and (2) an application example to compare between the performance of the two developed models in terms of efficiency and effectiveness. The following subsections present in details each of these evaluation examples and their main findings.

3.5.1 Evaluation Example (1)

The first application example was originally introduced by Zouein and Tommelein (1999) to analyze the dynamic site layout planning for a 4-day hypothetical project with a 20×10 site. The project duration is divided into two equal stages or Primary Time Frames (PTF): PTF-0-2 and PTF-2-4. Table 3.1 summarizes the project site facilities in this example and Figure 3.7 lists the travel cost rates (i.e., proximity weights) among the facilities in the two stages. To enable a comparison between the results generated by the present models and those provided by Zouein and Tommelein (1999), the same problem data and modeling assumptions were used. For example, the distances between facilities are represented as rectilinear (Manhattan) distances instead of the Euclidian distances used in the present model.

Table 3.1 Construction Facilities (Zouein and Tommelein 1999)

Facility	Dimension *Lx* x *Ly*	Time on Site	Relocation Cost	Fixed Positions (x, y, orient)
F1*	8 x 8	0 → 4	75	-
F2	2 x 1	0 → 2	0	(16, 8.5, 0)
F3*	2.8 x 2.8	2 → 4	50	-
F4	4 x 2	0 → 4	75	-
F5	4 x 2	0 → 2	0	(11, 6, 90)
F6	4 x 3	2 → 4	75	-
F7	4 x 2	2 → 4	50	-

* There is a min distance constraint in the X-direction of 8 units between facilities F3 and F1

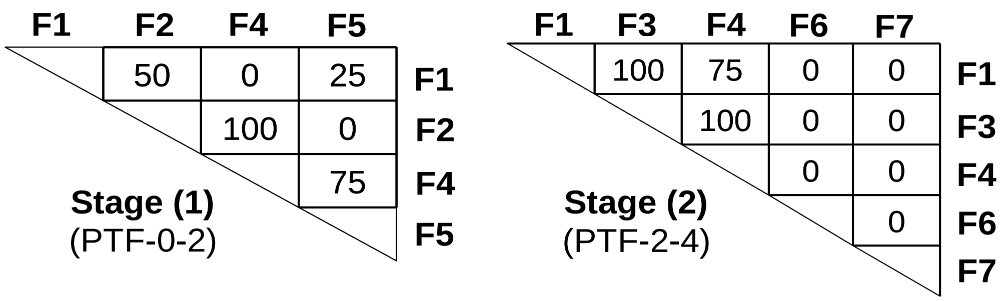


Figure 3.7 Travel Cost Rates (Zouein and Tommelein 1999)

The present model was used to analyze the application example in order to identify an optimal location for all position-able facilities, which include two in the first stage (F1 and F4), and five in the second stage (F1, F3, F4, F6, and F7). Accordingly, DSLP-GA model represents this problem using 14 decision variables (location and orientation decisions for each position-able facility), while DSLP-ADP model represents it using 7 decision epochs (each decision epoch represent the location and orientation decision of one of the position-able facilities). DSLP-GA model required providing the following run parameters: (1) population size of 1500 solutions; (2) 0.5 probability of crossover; and (3) 0.1 probability of mutation. On the other hand, another set of run parameters were identified for DSLP-ADP model, including: (1) the site grid pitch equals 0.5, (2) 500 ADP iterations, and (3) the constraint-violation factor (P) equals 10^5.

When solving this problem using DSLP-ADP model, the sequence of positioning facilities in each stage has a direct impact on the generated results. For example, one possible sequence of decision epochs for this example can be represented by [(F1, F4),(F1, F3, F4, F6, F7)]. This example sequence produces a site layout planning solution that is different from other possible sequences such as the one represented by [(F4, F1),(F7, F6, F4, F3, F1)]. Enumerating and analyzing all possible sequences of decision epochs in this site layout planning problem is impractical and can be computationally prohibitive. Alternatively, a set of ordering heuristics can be utilized to produce promising sequences of decision epochs similar to those presented by Zouein and Tommelein (1999). Ordering heuristics are often based on rules-of-thumb and human reasoning to prioritize decision epochs, such as placing first facilities with the largest area, or relocation cost. Table 3.2 summarizes the analyzed five decision sequences in this example. The optimization analysis was performed using a server with Dual Core Intel Xeon 1.8 GHz processors, 4 MB of cache memory, and a total of 4 GB of SDRAM. The computational times of this analysis using DSLP-ADP and DSLP-GA models were 2 and 4.5 minutes, respectively.

Table 3.2 Examined Sequences of Decisions for DSLP-ADP Model

No.	Sequence of Decision epochs	Site layout cost of optimal solution					
		DSLP-ADP			Zouein & Tommelein (1999)		
		1st stage	2nd stage	Total	1st stage	2nd stage	Total
1	(F1,F4), (F1,F3,F4,F6,F7)	2,900	4,850	**7,750**	2,250	5,635	**7,885**
2	(F1,F4), (F4,F3,F1,F6,F7)	2,975	5,037.5	**8012.5**	2,250	7,010	**9,260**
3	(F1,F4), (F3,F4,F1,F7,F6)	2,275	6,987.5	**9,262.5**	2,250	7,206.3	**9,456.3**
4	(F1,F4), (F6,F4,F3,F1,F7)	2,350	6,475	**8,825**	No feasible solution found		
5	(F1,F4), (F1,F3,F4,F7,F1)	2,900	4,850	**7,750**	2,250	5,635	**7,885**

The generated results by DSLP-GA and DSLP-ADP models are compared to those produced by Zouein and Tommelein (1999), as shown in Table 3.3. The results illustrate that the proposed models were capable of generating optimal site layout plans that globally outperformed those presented by Zouein and Tommelein (1999) because of their new capabilities. DSLP-ADP model generated better solution with lower total layout cost because of the new look-ahead capabilities that estimate and optimize the future effects of facility positioning in early stages on positioning decisions in future stages. DSLP-GA model generated better solution because of the simultaneous optimizing of the layout decisions in all construction stages. For example, the proposed models generated a globally optimal dynamic site layout plan for the first sequence of decisions (see Figure 3.8) that provides further reduction in the total layout cost, as shown in Table 3.3. This globally optimal solution was based on a site layout that is not necessarily the local optimal solution for the first stage, as shown in Table 3.3. The selection of this locally non-optimal plan in the first stage enabled the model to find the optimal plan in the second stage, which led to the global optimal layout plan for the entire project. It should be noted that DSLP-GA slightly outperformed DSLP-ADP in this example but with more computational time. Accordingly, a second example will be presented in the next section for further analysis and comparison between the performance of DSLP-ADP and DSLP-GA models in terms of efficiency and effectiveness.

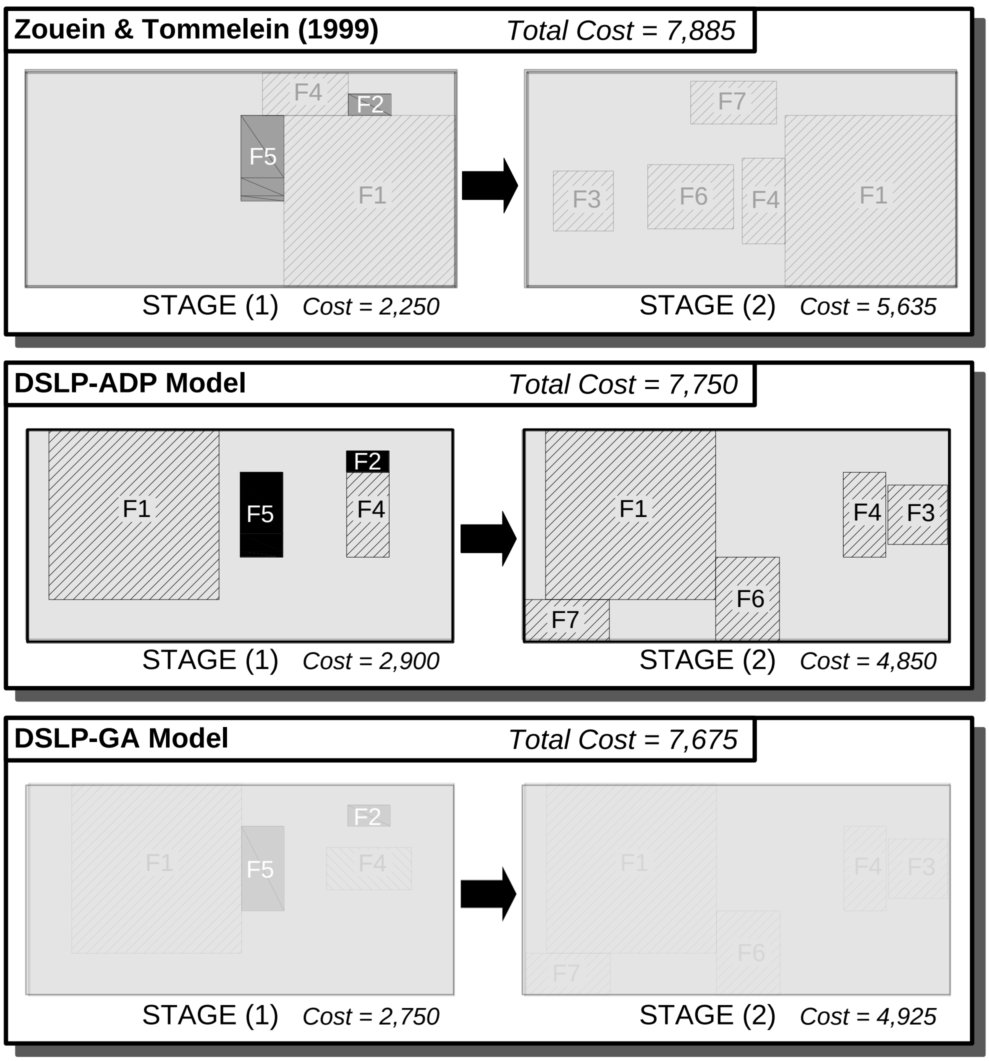


Figure 3.8 Generated Optimal Dynamic Layouts of Example 1

Table 3.3 Site Layout Optimization Results in Example 1

Model	Site layout cost of optimal solution		
	1st stage	2nd stage	Total
Zouein & Tommelein (1999)	2,250	5,635	**7,885**
DSLP-ADP	2,900	4,850	**7,750**
DSLP-GA	2,750	4,925	**7,675**

3.5.2 Evaluation Example (2)

The main objective of this example is to evaluate the performance of the two developed global optimization models for the problem of dynamic site layout planning in terms of two metrics: efficiency and effectiveness. The former metric was considered to measure the speed of the two models in terms of computational time, while the later metric was applied to measure the quality of the generated solutions in terms of the objective function. As shown in Table 3.4, the performance of the two developed models was evaluated using 18 experiments that consider various combinations of: (1) the number of construction stages that include 2, 3, and 4 stages; and (2) dynamic space needs over project stages. The experiments were analyzed using a server with Dual Core Intel Xeon 1.8 GHz processors, 4 MB of cache memory, and a total of 4 GB of SDRAM.

Table 3.4 Experiments Design in Evaluation Example 2

No.	No. of stages	Dynamic Space Needs				No. of Decision Variables
		1st stage	2nd stage	3rd stage	4th stage	
1	2	1F 3M 1S	2F 4M 1S	-	-	16
2		1F 4M 1S	2F 5M 1S	-	-	20
3		1F 5M 1S	2F 6M 1S	-	-	24
4		1F 6M 1S	2F 7M 1S	-	-	28
5		1F 7M 1S	2F 8M 1S	-	-	32
6		1F 8M 1S	2F 9M 1S	-	-	36
7	3	1F 3M 1S	2F 4M 2S	3F 5M 2S	-	28
8		1F 4M 1S	2F 5M 2S	3F 6M 2S	-	34
9		1F 5M 1S	2F 6M 2S	3F 7M 2S	-	40
10		1F 6M 1S	2F 7M 2S	3F 8M 2S	-	46
11		1F 7M 1S	2F 8M 2S	3F 9M 2S	-	52
12		1F 8M 1S	2F 9M 2S	3F 10M 2S	-	58
13	4	1F 3M 1S	2F 4M 2S	3F 5M 3S	4F 6M 3S	42
14		1F 4M 1S	2F 5M 2S	3F 6M 3S	4F 7M 3S	50
15		1F 5M 1S	2F 6M 2S	3F 7M 3S	4F 8M 3S	58
16		1F 6M 1S	2F 7M 2S	3F 8M 3S	4F 9M 3S	66
17		1F 7M 1S	2F 8M 2S	3F 9M 3S	4F 10M 3S	74
18		1F 8M 1S	2F 9M 2S	3F 10M 3S	4F 11M 3S	82

F = Fixed Facility, M = Moveable Facility, S = Stationary Facility

As shown in Table 3.5, DSLP-ADP model outperformed the DSLP-GA model in both effectiveness and efficiency. For all considered experiments, DSLP-ADP model generated optimal solutions with site layout costs less than those of the solutions generated by DSLP-GA model. As shown in Figure 3.9, the quality improvement provided by the ADP model over the GA model ranges from 6% to 25%. Moreover, this quality improvement of the performance in all considered experiments was achieved efficiently in less computational time, as shown in Figure 3.10. The outperformance of the ADP model refers to the fact that Dynamic Programming approach becomes a robust technique in optimizing dynamic problems such as dynamic site layout planning because of: (1) modeling the interdependencies and effects between the considered decision variables; and (2) estimating these inter-effects between the decision variables as a look-ahead capability. On the other hand, it should to be noted that GAs provide some capabilities and features that are not present in ADP and might be needed in future research for the problem of dynamic site layout planning. For example, GAs can be efficiently be used to perform multi-objective optimization of the DSLP problem where other objectives are considered beside site layout cost, such as security.

Table 3.5 Optimization Results in Evaluation Example 2

Experiment	No. of stages	Decision variables	Layout cost		Computational Time (min)	
			ADP	GA	ADP	GA
1	2	16	32.31	41.70	0.10	32.73
2		20	44.62	52.18	0.15	45.00
3		24	58.68	63.06	0.15	50.72
4		28	74.45	91.23	0.18	56.02
5		32	93.23	107.00	0.22	64.53
6		36	110.00	117.00	0.27	71.70
7	3	28	104.89	119.35	0.28	60.75
8		34	136.52	180.90	0.33	67.35
9		40	170.83	206.43	0.40	77.77
10		46	203.92	249.47	0.47	89.20
11		52	239.20	282.35	0.53	101.70
12		58	284.81	334.70	0.65	114.70
13	4	42	266.88	301.36	0.57	90.17
14		50	324.20	373.38	0.68	106.18
15		58	386.94	444.43	0.83	116.30
16		66	452.16	529.55	0.97	133.47
17		74	526.73	584.11	1.05	147.60
18		82	615.63	678.00	1.18	168.80

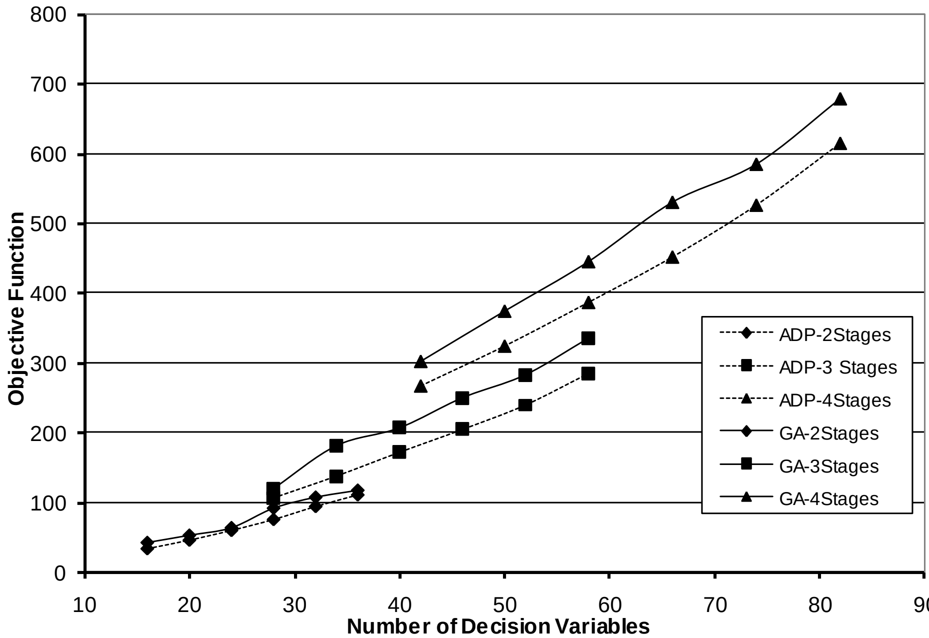


Figure 3.9 Comparison between Solutions Quality of DSLP-GA and DSLP-ADP Models

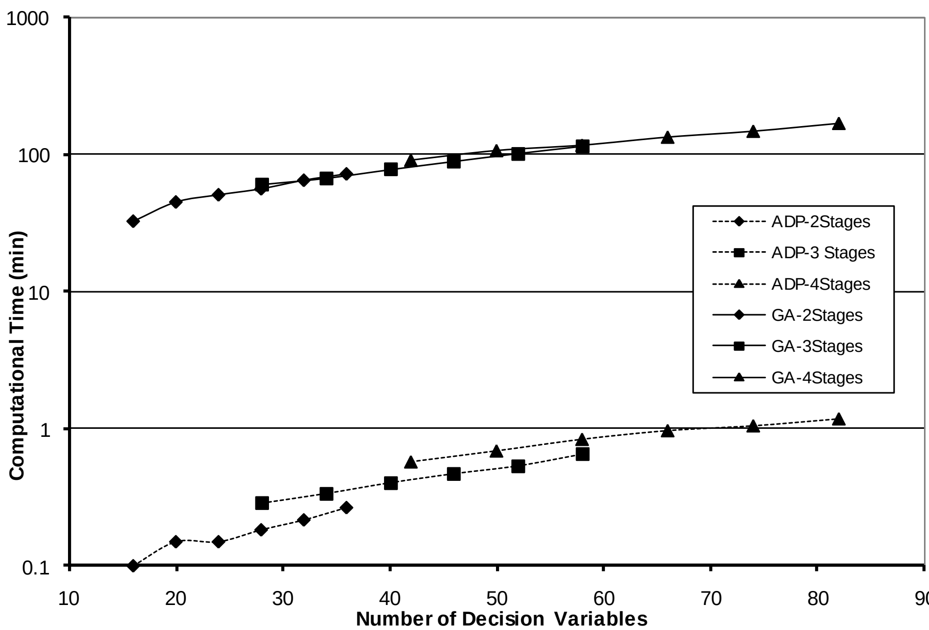


Figure 3.10 Comparison between the Computational Time of DSLP-GA and DSLP-ADP Models

3.6 Summary

This chapter presented the development of two global optimization models for the problem of dynamic site layout planning. The first model, DSLP-GA, is implemented using Genetic Algorithms that simultaneously optimize layout decision variables (locations and orientations) of temporary facilities in all construction stages. The second model, DSLP-ADP, is implemented using Approximate Dynamic Programming that optimizes layout decisions successively with novel look-ahead capabilities that estimate and optimize the future effects of facilities positioning in early stages on positioning decisions in future stages. The performance of the developed models was validated and investigated using two evaluation examples. The first example illustrated the robust performance of the developed models when compared to one of the previous models of dynamic site layout planning. The second example was designed to compare between the performances of the developed models in terms of efficiency and effectiveness. DSLP-ADP showed outstanding performance in both efficiency and effectiveness, compared to DSLP-GA, by generating more optimal solutions in shorter computational times. Nevertheless, DSLP-GA model presents a set of unique advantages over DSLP-ADP such as multi-objective optimization capabilities and its simple modeling approach. Because of the need for multi-objective optimization models in this research study, DSLP-GA is chosen to be utilized and incorporated in the other research tasks of this study to develop construction logistics planning and construction security models.

CHAPTER 4
CONSTRUCTION LOGISTICS PLANNING MODEL

4.1 Introduction

The main objective of this chapter is to present the development of a new construction logistics planning (CLP) model that is capable of integrating and optimizing critical planning decisions of material procurement and site layout planning on construction sites considering existing interdependencies and mutual impacts. As shown in Figure 4.1, existing material procurement models focus on procurement decisions without considering the availability of material storage space on dynamic construction site layouts. On the other hand, existing dynamic site layout planning models focus on site layout decisions without considering the impact of material procurement decisions on inventory levels and storage space needs. Overlooking these critical interdependencies between material procurement and site space availability can lead to serious project problems including material shortages, improper storage, poor and unsafe site layout, and productivity losses (Bell and Stukhart 1987; Thomas et al 1989; Jang et al 2007).

The present CLP model is designed to help contractors minimize material logistics costs using an integrated approach (see Figure 4.1) that simultaneously optimizes two categories of decision variables: (1) material procurement decisions that affect materials inventory levels and storage needs; and (2) dynamic layout decisions that indentify the dynamic locations of material storage areas and other temporary facilities over the project duration. Both categories of decision variables have a direct impact on the objective function that is designed to minimize the construction logistics costs, which include: (1) materials ordering cost, (2) financing cost, (3) stock-out cost, and (4) layout cost. The present CLP model is implemented using Genetic Algorithms (GA) (Deb et al 2001). GA has been widely used in many construction planning applications to find near optimal solutions to complex and large scale optimization problems by mimicking natural evolution (Li and Love 1997; Kandil and El-Rayes 2005; Khalafallah and El-Rayes 2008). GA is an iterative algorithm in which a population of abstract representation of decision variables (called chromosome) that evolves toward a better solution of decision variables utilizing natural processes such as selection, crossover, mutation, and elitism (Goldberg 1989). The algorithm starts by an initial population of chromosomes randomly generated that evolves by applying the following steps iteratively: (1) evaluating the fitness of each chromosome using the objective function; (2) selecting a group of chromosomes based on their fitness to produce a more fit offspring; and (3) generating a new population using various genetic operators (crossover, mutation, and elitism). The following sections describe in more details the two categories of decision variables as well as the optimization objective function of the present CLP model.

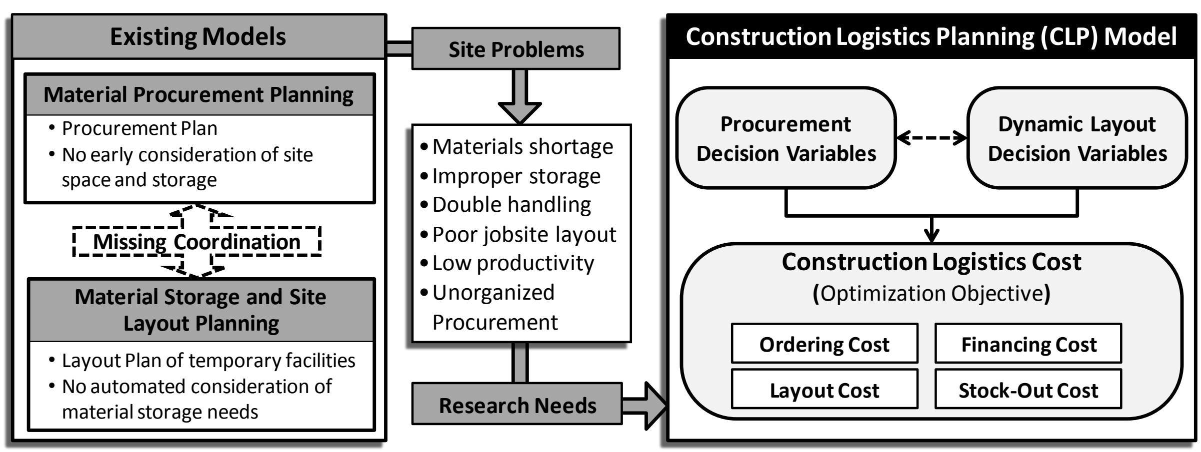


Figure 4.1 Construction Logistics Planning Model

4.2 Procurement Decision Variables

The planning of material procurement and supply in the present model is accomplished by identifying the optimal ordering period of each material that is changing dynamically to consider the fluctuating demand over the project duration. In the present model, the construction duration is divided into *T* stages that can be specified by project planners to account for the changing demand rate of materials and site space availability. As shown in Figure 4.2, material procurement in each stage (*t*) is formulated as a fixed-ordering-period (FOP) system that replenishes the inventory at the beginning of fixed intervals, when new orders are acquired to cover the demand for the succeeding intervals (Magad and Amos 1995). Accordingly, procurement decision variables in the present model are represented by the fixed-ordering-period ($FOP_{m,t}$) of each material (*m*) in every construction stage (*t*). In the present model, ordering quantities are unequal with uniform replenishment periods ($FOP_{m,t}$) that can take any duration starting from one day in the case of Just-In-Time (JIT) system to longer durations in the case of traditional inventory systems, as shown in Figure 4.2. By considering the shortest ordering period (one day), the inventory is eliminated by having daily material procurement that satisfies the day-to-day material demand. On the other hand, considering longer fixed-ordering-periods creates inventory stocks that are replenished over uniform intervals, as shown in Figure 4.2. It should be noted that the values of the procurement decisions in the present model are constrained by the supplier capacity to ensure that the quantities of the generated orders do not exceed the maximum amount that the supplier can provide in a single order.

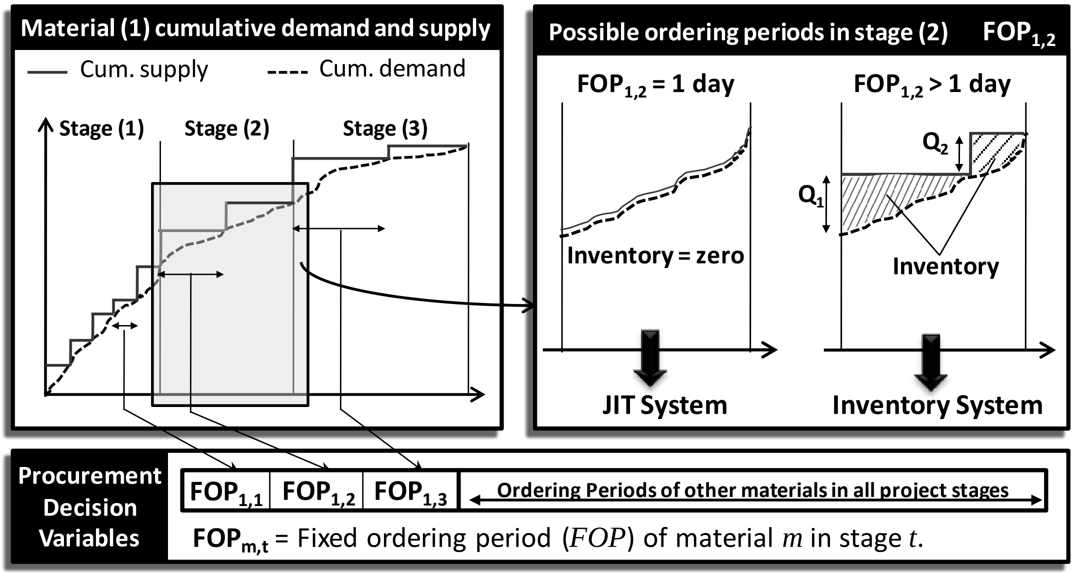


Figure 4.2 Procurement Decision Variables

The present model is designed to consider the impact of the aforementioned procurement decisions ($FOP_{m,t}$) on material storage space needs in two main steps. First, the supply schedule of each material m (i.e., delivery quantities and dates) is generated for construction stage (t) based on the values of the fixed-ordering-periods ($FOP_{m,t}$). For example, the inventory of material (m) in stage (t) shown in Figure 4.3 is replenished by three unequal-quantity orders over three equal periods. It should be noted that the last replenishment interval in a stage is the minimum of the selected fixed-ordering-period and the remaining time in the corresponding stage. Second, storage space needs are identified based on the maximum inventory level and materials footprint schedules. The maximum inventory level is the largest quantity of the material stored on site during the corresponding stage, which is determined in the present model based on the largest order quantity in the generated procurement plan. The identified maximum inventory level is then used to estimate the material storage needs based on the *materials footprint schedules*, as shown in Figure 3. In the present model, materials footprint schedules are specified by construction planners to define the dimensions (*Lx* and *Ly*) of materials storage areas for different inventory quantities (see Figure 4.3).

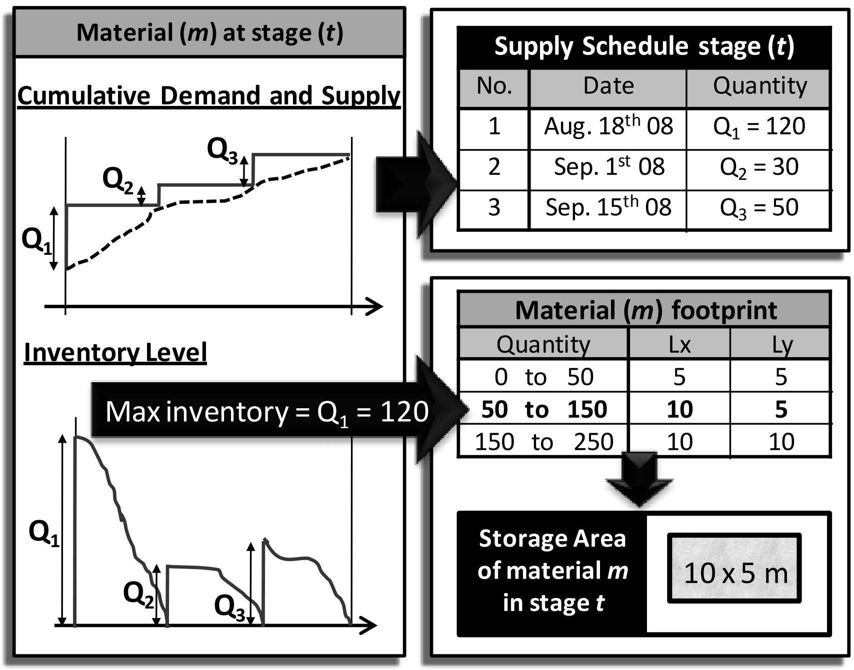


Figure 4.3 Impact of Procurement Decision on Material Storage Needs

4.3 Dynamic Layout Decision Variables

In the present model, dynamic layout decision variables are designed to identify the dynamic layout (i.e., locations and orientations) of (1) material storage areas; and (2) temporary facilities on site, as shown in Figure 4.4. First, the model identifies the optimal layout decisions of material storage areas based on their space needs that are estimated using the aforementioned procedure that considers the impact of procurement decisions (see Figure 4.3). The number of decisions variables representing material storage areas in the present model depends on the number of stages and the number of materials *m* required in each stage *t*, as shown in Figure 4.4. For example, the following ten decision variables are needed to represent the layout of material storage areas for the example in Figure 4.4: (1) two decision variables for the location and orientation of storage area of material 1 in the first stage; (2) four decision variables for the locations and orientations of materials 1 and 2 in the second stage; and (3) four decision variables for the locations and orientations of materials 1 and 2 in the third stage. Possible site locations are generated based on a grid of locations that depends on a grid pitch defined by planners, while the orientation angle can be either 0 or 90 degrees, as shown in Figure 4.4.

In addition to material storage areas, the model also identifies the optimal layout of other temporary facilities on site such as office trailers and batch plants, as shown in Figure 4.4. The present CLP model categorizes construction temporary facilities into moveable and stationary facilities (El-Rayes and Said 2008). Moveable facilities can be relocated at the beginning of each construction stages with additional relocation cost, such as office trailers and fabrication areas. Stationary facilities cannot be relocated after they are positioned because of the significant time and cost required for their relocation, such as tower crane and batch plants. Accordingly the layout decision variables of temporary facilities are the location and orientation of: (1) every moveable facility in each stage during which the facility exists on site; and (2) every new stationary facility in each construction stage. For example, the layout of temporary facilities shown in Figure 4 includes the following ten decision variables: (1) two decision variables for the location and orientation of the first facility (stationary) that will exist for the whole project duration; (2) four decision variables for the locations and orientations of the second facility (moveable) in the first and second stages; and (3) four decision variables for the locations and orientations of the third facility (moveable) in the second and third stages. It should be noted that the layout of both storage areas and temporary facilities should comply with a set of geometric constraints in order to: (1) position all facilities and storage areas within the boundaries of the construction site; (2) prevent overlaps between any pair of facilities and/or storage areas; (3) maintain operational or safety distance between facilities and/or storage areas; and (4) consider the existence of any exclusion zones onsite (Zouein and Tommelein 1999; El-Rayes and Said 2008).

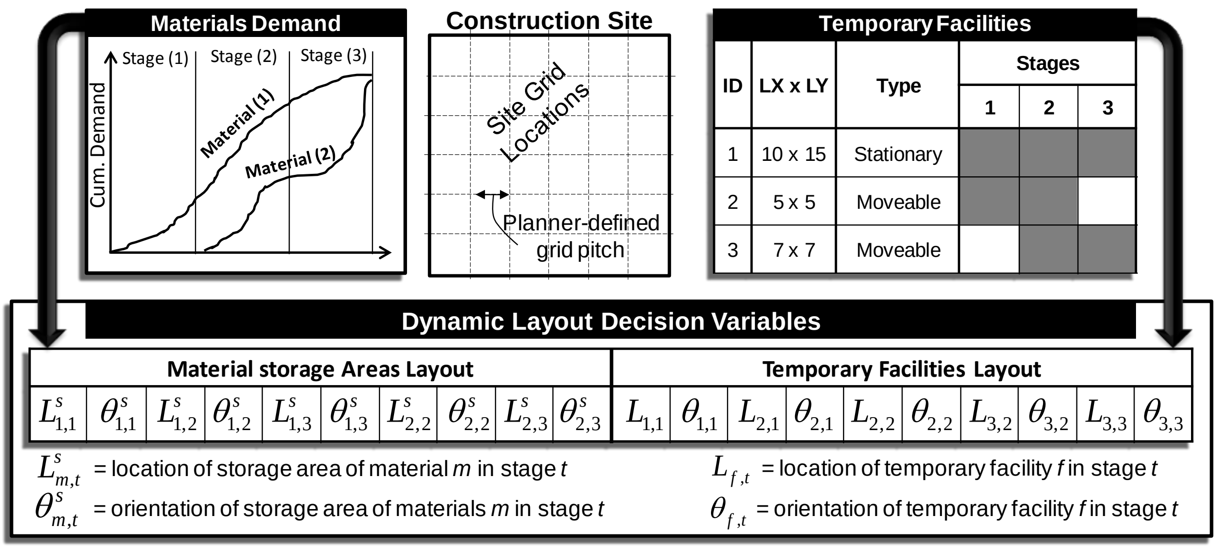


Figure 4.4 Dynamic Layout Decision Variables in the CLP Model

4.4 Construction Logistics Cost

The present CLP model is designed to minimize construction logistics costs that are affected by the aforementioned procurement and layout decision variables. As shown in Equation 4.1, construction logistics costs in the present model (*CLC*) include four main cost components: (1) ordering cost (*OC*) that represents the cost to physically acquire the materials from suppliers and transport them to the construction site; (2) financing cost (*FC*) that includes interest on the locked up capital in materials inventories; (3) stock-out cost (*SC*) that estimates project delay costs due to material shortages, if any; and (4) layout cost (*LC*) that accounts for material handling costs and resource travel costs on site. The present model seeks to minimize these construction logistics costs by identifying optimal solutions for the aforementioned procurement and layout decision variables. The following subsections describe each of these four cost components and how they are affected by procurement and layout decisions.

$$CLC = OC + FC + SC + LC \tag{4.1}$$

Where,

CLC = construction logistics costs;

OC = ordering cost;

FC = financing cost;

SC = stock-out cost; and

LC = layout cost.

4.4.1 Ordering Cost

Ordering cost (OC) represents the purchase cost of materials and their delivery from suppliers to the construction site (Blanchard 2007). As shown in Equation 4.2, both material purchase and delivery costs depend on the number of material orders and their quantities which are identified based on the aforementioned procurement decisions. Small order quantities results in high purchase cost because of the loss of potential discounts provided by suppliers for larger order quantities. Moreover, small order quantities may result in high delivery costs because of under-utilized trucks with loads less than their maximum capacities. As shown in Figure 4.5, a simplified example is provided to illustrate the impact of procurement decisions on ordering cost, where it is required to supply 600 units of material *m* in stage *t*. In this example, two options of procurement plan are considered: (1) twelve equal deliveries of 50 units; or (2) two deliveries of 300 units. The example illustrates that the first option leads to a higher ordering cost because it supplies the required 600 units using more deliveries with smaller quantities.

$$OC = \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{n=1}^{NOR_m^t} \left(Q_i \times PCR_m^t(Q_n) + DLC_m^t(Q_n) \right) \qquad (4.2)$$

Where,

T = number of project stages;

M = number of project materials;

NOR_m^t = number of orders of material *m* in stage *t*;

Q_n = order quantity of order *n*;

$PCR_m^t(Q_n)$ = purchase cost rate of material *m* in stage *t* with Q_n order quantity; and

$DLC_m^t(Q_n)$ = delivery cost of material *m* in stage *t* with Q_n order quantity.

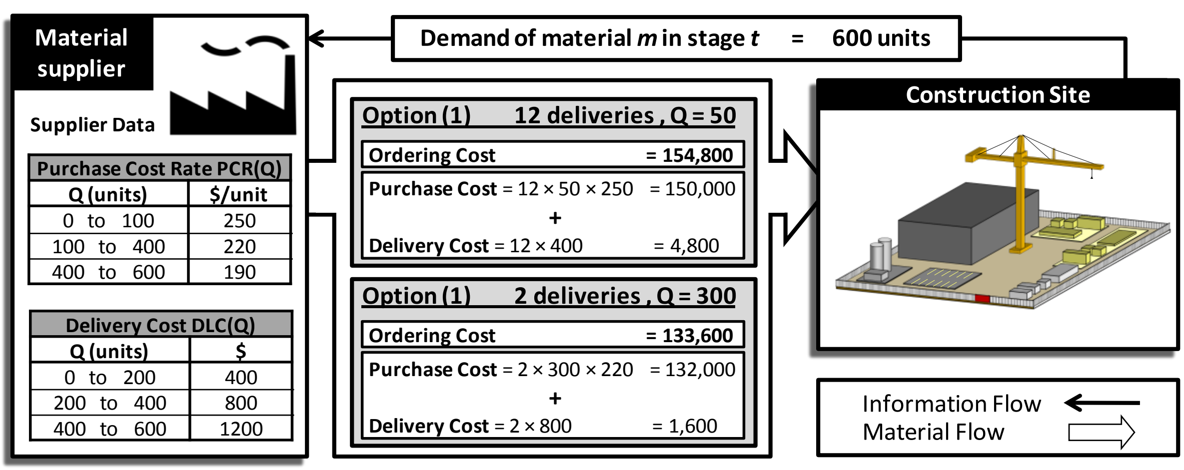


Figure 4.5 Impact of Procurement Decisions on Ordering Costs

4.4.2 Financing Cost

Financing cost (*FC*) is the cumulative interest on working capital of the contractor tied up in the purchased inventories of materials stored on site (Polat et al. 2007). Financing cost represents: (1) the return on the contractor's money tied up in materials inventory if it is invested elsewhere such as a savings account; or (2) the amount of interest that the contractor pays if this tied capital is secured from a loaning institution. As shown in Equation 4.3, the present CLP model calculates the cumulative financing cost as the sum of the interest paid on the monetary value of the daily inventory of each material over the project duration using a daily interest rate defined by the planner. The inventory level of material *m* in a calendar day *d* is calculated as the difference between the cumulative supply (CS_d^m) and cumulative demand (CD_d^m) of the corresponding material and day. It should be noted that the cumulative supply is solely affected by the aforementioned procurement decision variables ($FOP_{t,m}$), where longer $FOP_{t,m}$ leads to larger materials inventories (see Figure 4.2).

$$FC = \sum_{d=1}^{NCD}\left(\sum_{m=1}^{M}\left(CS_d^m - CD_d^m\right) \times PCR_m^{avg} \times DIR\right) \tag{4.3}$$

Where,

NCD = number of project days;

CS_d^m = cumulative supply of material *m* in day *d*;

CD_d^m = cumulative demand of material *m* in day *d*;

PCR_m^{avg} = average purchase cost rate of material *m*; and

DIR = project daily interest rate.

4.4.3 Stock-out Cost

Stock-out cost (*SC*) represents project delay costs that may occur as a result of delayed materials delivery and depleted materials inventory (Magad and Amos 1995). The present model utilizes a newly developed algorithm of estimating materials-related project delay (*MRPD*) considering the following input: (1) number of project's working days (*NWD*); (2) number of construction activities (*I*); (3) project baseline schedule that includes activities early start and finish times (ES_i and EF_i); (4) number of construction materials (*M*); (5) delivery average delays of construction materials (DAD_m) that are estimated based on historical delivery records and/or suppliers input; (6) materials assignments to project activities ($MA_{m,i}$); and (7) quantities of materials deliveries on every working day ($MD_{m,d}$), which are generated based on the aforementioned procurement decision variables ($FOP_{m,t}$).

The new algorithm of estimating materials-related project delay costs (*MRPD*) comprises three nested loops, as shown in Figure 4.6. The first loop iterates over all construction activities ($i=1$ to I) to check if a delay occurs for each activity *i* on day *d* due to late delivery of material *m*. Activity *i* is considered delayed on day *d* due to late delivery of material *m* if the following four conditions are satisfied simultaneously: (1) activity *i* is in progress on day *d* (i.e. $ES_i \leq d$ *AND* $EF_i \geq d$); (2) material *m* is utilized by activity *i* and therefore has a non-zero assignment value to activity *i* (i.e. $MA_{m,i} > 0$); (3) a delivery of material *m* is scheduled on day *d* based on the generated procurement decision variables ($FOP_{m,t}$); and (4) delivery average delay of material *m* (DAD_m) is bigger than the current estimated delay ($Delay_i$) caused by late delivery of other materials. If all previous conditions are satisfied, the estimated delay of activity *i* is set to the delivery average delay of material *m* (DAD_m). The second loop repeats the first loop for all construction materials ($m=1$ to M) to estimate activities delays because of the combined delay of all materials on specific day *d*. The third loop progressively iterates the second loop for all project working days (*d=1* to *D*), where project schedule is updated at the end of each iteration based on estimated activities delay ($Delay_i$) using critical path method (CPM) calculations. This algorithm ends by calculating the materials-related project delay (*MRPD*) as the difference between: (1) the estimated delayed finish time of the project which is calculated as the latest finish time of all project activities due to the late delivery of materials ($\max_i\left(\overline{EF_i}\right)$); and (2) the project baseline finish time which is calculated as the latest finish time of all project activities ($\max_i\left(EF_i\right)$), as shown in Equation 4.4. Accordingly, Stock-out cost (*SC*) is calculated, as shown in Equation 4.5, using this estimated materials-related project delay (*MRPD*) and the project liquidated damage (*LQD*) and/or time-dependent indirect costs (*TDIC*).

$$MRPD = \max_i\left(\overline{EF_i}\right) - \max_i\left(EF_i\right) \tag{4.4}$$

$$SC = MRPD \times \left(LQD + TDIC\right) \tag{4.5}$$

Where,

MRPD = materials-related project delay;

EF_i = early finish of activity *i* in the baseline project schedule;

$\overline{EF_i}$ = expected early finish of activity *i* after considering late delivery of materials; *LQD* = liquidated damage cost; and

TDIC = time-dependent indirect cost.

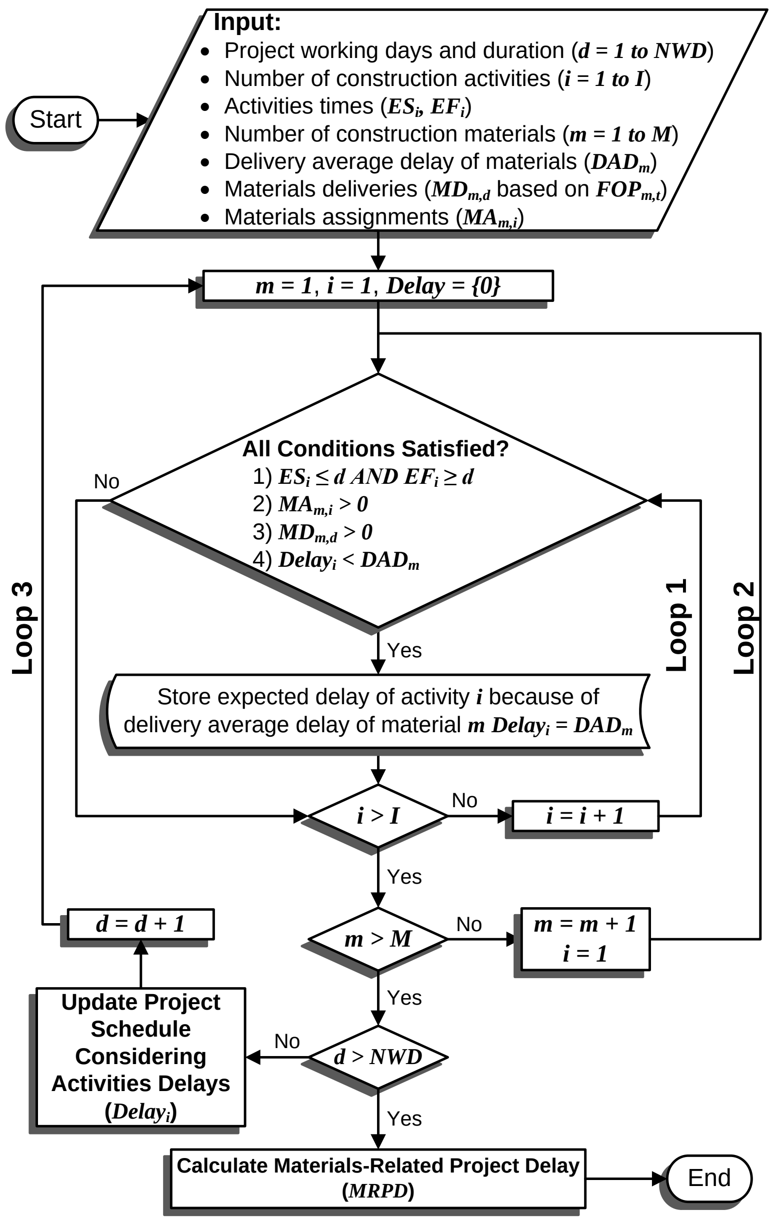


Figure 4.6 CLP Model Algorithm for Computing Material-Related Project Delay (MRPD)

4.4.4 Layout Cost

Layout cost (LC) represents the travel costs of resources between site facilities and/or storage areas and the costs of site layout reorganization over the project duration. As shown in

Equation 4.6, the layout cost in the present CLP model is composed of three main cost components: materials handling cost (*MHC*), resources travel cost (*RTC*), and site reorganization cost (*SRC*). First, materials handling cost (*MHC*) represents the travel cost of site handling equipments or laborers that cyclically transport construction materials from their storage areas to buildings under construction and/or site temporary facilities (e.g. fabrication area). As shown in Equations 4.7 and 4.8, the materials handling cost is calculated using: (1) the estimated quantity of materials that needs to be transported from each storage area to every site facility in all stages ($Q^t_{m,f}$); (2) the travel cost rates of handling crews which are represented by their handling capacity ($q^r_{m,f}$) that identifies the quantity of material that can be transported in one crew trip, crew hourly cost rate (HCR_r), and crew travel speed (v_r); and (3) the Euclidian traveling distances ($D^t_{m,f}$). Second, the resource travel cost (*RTC*) is calculated for other non-material handling resources (e.g., equipment, labor, and supervision personnel) moving between temporary facilities and/or buildings under construction (see Equation 4.9). The resource travel cost (*RTC*) is calculated based on: (1) the travel cost rates between each pair of site facilities in every stage ($C^t_{f,g}$); and (2) the Euclidian traveling distances ($D^t_{f,g}$). Third, the site reorganization cost (*SRC*) represents the extra cost paid by the contractor to change site layout at the beginning of each construction stage by relocating some or all moveable facilities. As shown in Equation 4.10, relocation cost occurs for a moveable facility if it is either moved from its location in the preceding stage (i.e. $D^{t,t-1}_f > 0$) or if its orientation angle is changed (i.e. $\theta^t_f \neq \theta^{t-1}_f$).

$$LC = MHC + RTC + SRC \tag{4.6}$$

$$MHC = \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{f=1}^{NF_t} C_{m,f}^{t} \times D_{m,f}^{t} + \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{f=1}^{NB_t} C_{m,f}^{t} \times D_{m,f}^{t} \tag{4.7}$$

$$C_{m,f}^{t} = \frac{2 \times (Q_{m,f}^{t} / q_{m,f}^{r}) \times HCR_r}{v_r} \tag{4.8}$$

$$RTC = \sum_{t=1}^{T}\sum_{f=1}^{NF_t-1}\sum_{g=f+1}^{NF_t} C_{f,g}^{t} \times D_{f,g}^{t} + \sum_{t=1}^{T}\sum_{f=1}^{NF_t}\sum_{g=1}^{B_t} C_{f,g}^{t} \times D_{f,g}^{t} \tag{4.9}$$

$$SRC = \sum_{t=1}^{T}\sum_{f=1}^{NF_t^M} E_f \times RC_f \times IF\left\{D_f^{t,t-1} > 0 \quad OR \quad \theta_f^t \neq \theta_f^{t-1}\right\} \tag{4.10}$$

Where

LC = layout cost;

MHC = material handling cost:

RTC = resource traveling cost;

SRC = site reorganization cost;

T = number of project stages;

M = number of project materials;

NF_t = number of temporary facilities used in stage t;

NB_t = number of buildings under construction in stage t;

$C_{f,g}^{t}$ = travel cost rate of resources between facilities f and g in stage t;

$D_{f,g}^{t}$ = Euclidian distance between facilities f and g in stage t;

$D_f^{t,t-1}$ = Euclidian distance between facility *f's* positions in stages t and t-1;

$Q_{m,f}^{t}$ = estimated quantity of material m required in facility f in stage t;

$q_{m,f}^{r}$ = handling capacity of handling crew r handling material m to facility f;

HCR_r = hourly cost rate of handling crew r (\$/hour);

v_r = speed of handling crew r (m/hour);

E_f = facilities existence factor equals to 1 if the moveable facility f exists in previous stage t-1, and 0 otherwise;

RC_f = relocation cost of moveable facility f; θ_f^t = orientation angle of facility f in stage t; and

IF{condition} = a conditional function that returns 1 if the inside condition is satisfied, 0 otherwise.

4.5 Model Evaluation

An application example is used to evaluate and demonstrate the capabilities of the present CLP model in integrating and optimizing the critical planning decisions of material procurement and material storage on construction sites. As shown in Figure 4.7, the example involves the construction of two office buildings over three stages where the construction of the first building B1 is planned to be completed in a duration that covers the three stages while the construction of the second building B2 is planned to start in the second stage. For the purpose of illustration, three materials are considered in this example, which include reinforcing steel (rebar), autoclaved cellular concrete (ACC) blocks, and glass curtain walls. Cost rates of materials and handling crews are estimated using RSMeans Building Construction Cost Data (RSMeans 2001). Figure 4.7 depicts the cumulative demand of the three considered materials where the reinforcing steel is required in all stages while the concrete block masonry and curtain walls are required in the second and third stages. In this example, the construction project requires the utilization of seven temporary facilities such as office trailers and fabrication areas as shown in Table 4.1. The present CLP model is used in this example to generate the optimal procurement and layout decisions in order to minimize total logistics cost.

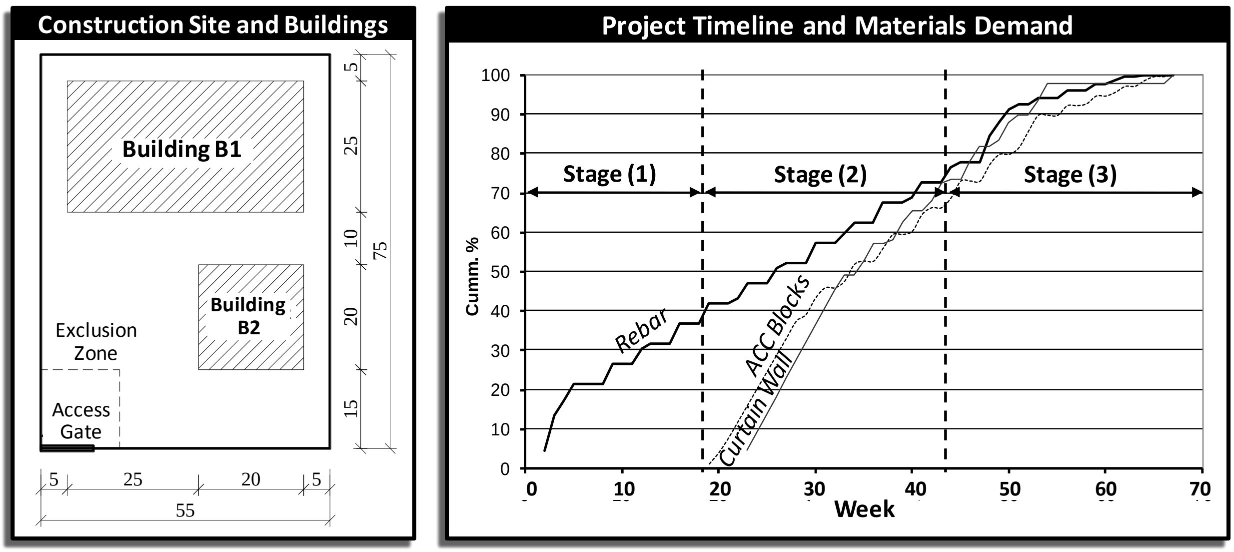


Figure 4.7 Geometry and Time Data of the Application Example

Table 4.1 Geometry and Time Data of Site Facilities

	ID	Description	dimensions		Time on site			Fixed position	
			Lx	Ly	T1	T2	T3	x	y
Fixed Facilities	B1	Building (1)	45	25	√	√	√	27.5	57.5
	B2	Building (2)	20	20	-	√	√	40	25
	G	Site Gate	10	1	√	√	√	5	0
	ID	Description	dimensions		Time on site			Type *	Relocation Cost
			Lx	Ly	T1	T2	T3		
Temporary Facilities	F1	Tower Crane	8	8	√	√	√	S	N.A.
	F2	Office trailer (1)	14	4	√	√	√	M	6,000
	F3	Office trailer (2)	11	3	-	√	√	M	4,000
	F4	Fabrication Area	15	10	√	√	√	M	2,000
	F5	Dump Area	15	15	√	√	-	M	0
	F6	Lay-Down Area	10	10	√	√	√	M	3,000
	F7	Labor Rest Area	5	5	√	√	√	M	500

** S = Stationary   M = Moveable*

In order to optimize the planning of material procurement and storage in this example, the present CLP model requires construction planners to provide the following input data: (1) the construction site geometry including the dimensions and locations of buildings under construction and site boundaries, as shown in Figure 4.7; (2) the project stages and cumulative demand of each material over time, as shown in Figure 4.7; (3) the dimensions and relocation costs of each temporary facility as shown in Table 4.1; (4) the travel cost rates between site facilities $\left(C_{ij}^{t}\right)$ as shown in Table 4.2; (5) the purchase cost, delivery cost, and storage footprint data of each material, as shown in Table 4.3; (6) on-site materials handling quantities and cost data as shown in Table 4.4; (7) the layout constraints imposed on temporary facilities and material storage areas as shown in Table 4.5; (8) layout grid pitch which is specified to be 1 m in this example; (9) daily project interest rate (*DIR*) which is estimated to be 0.03%; (10) project liquidated damage (*LQD*) which is estimated to be $25,000/day; (11) time-depended indirect cost (*TDIC*) which is estimated to be $5,000/day; (12) possible values of fixed-ordering-period (FOP), which are 1, 7, 14, or 21 days; and (13) delivery average delay (DAD_m) of each material, which is estimated to be 0.7, 0.3, and 2 for the rebar, AAC blocks, and curtain walls, respectively.

Table 4.2 Travel Cost Rates ($/m) among Facilities in all Stages

Facility	Facility (j)									
(i)	B1	B2	G	F1	F2	F3	F4	F5	F6	F7
B1	0	0	0	150	50	50	90	20	70	15
B2	-	0	0	100	40	40	60	15	40	15
G	-	-	0	0	2	2	1	30	0	0
F1	-	-	-	0	0	0	30	4	25	0
F2	-	-	-	-	0	20	5	0	5	0
F3	-	-	-	-	-	0	5	0	5	0
F4	-	-	-	-	-	-	0	0	30	0
F5	-	-	-	-	-	-	-	0	0	0
F6	-	-	-	-	-	-	-	-	0	0
F7	-	-	-	-	-	-	-	-	-	0

Table 4.3 Ordering Costs and Storage Footprints of Construction Materials

ID	Material	unit	Purchase Cost ($/unit)			Delivery Cost ($)		Storage Footprint		
			Stage t	**Quantity** Q	**rate** $PCR^t(Q)$	**Quantity** Q	**Cost** $DLC^t(Q)$	**Quantity** Q	**Lx** (m)	**Ly** (m)
M1	Rebar	ton	1	0 → 100	650	0 → 25	600	0 → 32	15	2
			1	100 → 200	550	25 → 50	1200	32 → 64	15	4
			2,3	0 → 100	750	50 → 75	1800	64 → 96	15	6
			2,3	100 → 200	650	75 → 100	2400	96 → 128	15	8
						100 → 125	3000	128 → 160	15	10
						125 → 150	3600	160 → 192	15	12
						150 → 175	4200	192 → 224	15	14
						175 → 200	4800			
M2	AAC Blocks	1000 blocks (M)	1 → 3	0 → 10	1,100	0 → 3	600	0 → 1	2.5	2.5
			1 → 3	10 → 30	950	3 → 6	1200	1 → 2	5	2.5
						6 → 9	1800	2 → 4	5	5
						9 → 12	2400	4 → 6	7.5	5
						12 → 15	3000	6 → 9	7.5	7.5
						15 → 18	3600	9 → 12	10	7.5
						18 → 21	4200	12 → 16	10	10
						21 → 24	4800	16 → 20	12.5	10
						24 → 27	5400	20 → 25	12.5	12.5
						27 → 30	6000	25 → 30	15	12.5
M3	Curtain Wall	m^2	1 → 3	0 → 1500	210	0 → 250	1000	0 → 250	5	5
						250 → 500	2000	250 → 500	10	5
						500 → 750	3000	500 → 750	10	10
						750 → 1000	4000	750 → 1000	15	10
						1000 → 1250	5000	1000 → 1250		
						1250 → 1500	6000	1250 → 1500		

Table 4.4 Materials On-Site Handling Quantities and Cost Data

Material m	**unit**	**Facility** i	**Stage** t	**Required Quantity** Q_{mi}^{t}	**Handling Equipment** r	**Handling Quantity** q_{mi}^{r}	**Travel Speed** v_r (m/hr)	**Hourly Cost** HCR_r ($/hr)	**Travel Cost Rate** C_{im}^{t} ($/m)
Rebar	ton	B1	1	286.5	Tower Crane	2	5,000	200	11.46
		B1	2	280					11.20
		B1	3	88					3.52
		B2	3	124					4.96
AAC Blocks	M	B1	2	97.5		0.5			15.60
		B1	3	30.5					4.88
		B2	3	17.83					2.85
Curtain Wall	m^2	B1	2	4541.67		4.5			80.74
		B1	3	1998.33					35.53
		B2	3	140					2.49

Table 4.5 Site Layout Planning Constraints

Distance Constraints			
Purpose	**Type**	**Facilities**	**Distance (m)**
Safety	Min	B1, F2	5
	Min	B1, F3	5
	Min	B1, F7	5
	Min	B2, F2	5
	Min	B2, F3	5
	Min	B2, F7	5
	Min	F1, F2	15
	Min	F1, F3	15
	Min	F1, F7	15
Operational	Max	F1, F2	30
	Max	F1, F3	30
	Max	F1, B1	30
	Max	F1, B2	30
	Max	F1, F4	30
	Max	F1, F6	30
	Max	F1, M1	30
	Max	F1, M2	30
	Max	F1, M3	30
	Max	F2, B3	5
	Min	M3, M1	5
	Min	M3, M2	5
	Min	M3, B1	5
	Min	M3, B2	5

Exclusion Zone Constraints (Operational)				
Facility	**X1**	**X2**	**Y1**	**Y2**
All site facilities	0	15	0	15

The present CLP model was used to analyze the aforementioned input data to generate an integrated optimal material procurement and layout plan for the application example. Using a GA population size of 1500, the present model generated an optimal plan with a total cost of $2,349,646 based on the identified optimal procurement decision variables shown in Table 4.6 and the optimal layout decision variables illustrated by the dynamic layout plan in Figure 4.8. The model was used to evaluate the fitness (construction logistics cost) by performing the following steps for each solution examined by the GA optimization tool in order to calculate: (1) the order quantities of each material during every stage based on the generated FOP and the material's demand in that stage, as shown in Table 4.6; (2) the ordering costs based on the order quantities identified in step 1 and the suppliers purchase and delivery costs listed in Table 4.3; (3) the financing cost using Equation 3 based on the cumulative materials demand (shown in Figure 7) and the cumulative supply which is dependent on the generated FOP values; (4) the stock-out cost using Equation 4.5 and the aforementioned algorithm (see Figure 4.6) for calculating material-related project delay (MRPD); (5) the maximum inventory for each material *m* in every stage *t* based on the generated $FOP_{m,t}$ and material's demand; (6) the storage space needs and dimensions for each material in every stage (see Table 4.6) based on the planner-defined footprint schedules and the value of the FOP; and (7) the layout costs using Equations 4.6 through 4.10 considering the values of layout decision variables (locations and orientations) for all storage areas and temporary facilities.

Analyzing the generated optimal results for this example reveals that material procurement decisions are greatly affected by (1) the criticality of construction activities consuming the material; and (2) site space availability. First, materials for construction activities on the critical path required long fixed-ordering-periods (*FOP*) as shown in the optimal procurement decisions in Table 4.6. Longer material FOP values were generated for these critical activities to ensure the availability of larger inventories to minimize materials-related project delays. For example, the optimal FOP for the rebar material was identified by the model to be 21 days in the three stages because all the rebar activities in this example were on the project critical path resulting in zero delivery slacks. Second, the site space availability had also a significant impact on the generated optimal procurement decisions in Table 4.6. For example, shorter FOP values for the AAC blocks and curtain walls (1 and 7 days, respectively) were generated in the second stage because of the limited site space. On the other hand, longer FOP values were generated for the same materials in the third stage because more site space became available as facility F5 (dump area) was no longer needed. It should be noted that the present CLP model considers and optimizes the tradeoffs among all logistics cost items (i.e., ordering, financing, and stock-out costs) in identifying the optimal material procurement and site layout decisions.

Analyzing the generated optimal results reveals also that dynamic site layout decisions are affected by (1) procurement decisions and material storage space needs; and (2) site layout constraints. As shown in Figure 4.8, dynamic site layout decisions are affected by the procurement decisions their storage space needs, as shown in Table 4.6. Similarly, the dynamic site layout decisions are affected by the distance and zone constraints shown in Table 4.5 that are imposed to represent safety and/or operational issues, such as: (1) positioning the site office trailers (F2 and F3) and labor rest areas (F7) at least 5 meters away from building B1 and B2 and 15 meters away from the tower crane (F1) to mitigate the hazards of falling objects; (2) positioning the tower crane (F1) as shown in Figure 8 to comply with operational distance constraint of having buildings B1 and B2 within the crane jib reach (30 meters); and (3) positioning all temporary facilities and storage areas out of the gate exclusion zone to prevent blocking site access point.

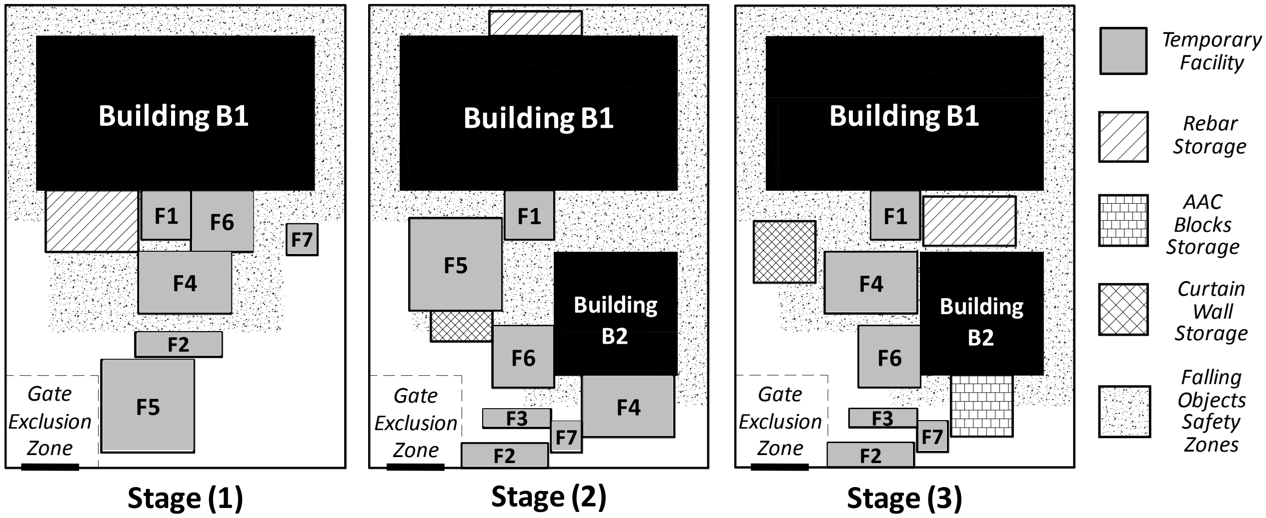


Figure 4.8 Generated Dynamic Layout Plan Considering Procurement Material Decisions

Table 4.6 Optimal Values of Procurement Decision Variables and Resulting Logistics Costs

Material (m)	Stage (t)	$FOP_{m,t}$ (days)	Procurement Plan		Max Inventory	Storage area (m × m)	Logistics Cost		
			Date	Quantity			Ordering	Financing	Stock-Out
Rebar	1	21	8/19/08 ……… 11/14/08	156.25 …….. 40	156.25	15 × 10	178,400	699.85	
	2	21	12/22/08 ……… 5/18/09	60 …….. 40	60	15 × 4	218,400	586.65	
	3	21	6/8/09 ……… 11/2/09	40 …….. 2.5	105.5	15 × 8	155,650	393.02	
AAC Blocks	2	1	12/25/08 ……… 6/2/09	0.833 …….. 1.25	N.A. (JIT)		156,950	0	60,000 (2 days delay)
	3	21	6/8/09 ……… 11/2/09	10 …….. 4.08	13	10 × 10	63,213	127.71	
Curtain Wall	2	7	1/9/09 ……… 6/5/09	60.56 …….. 60.56	423.89	10 × 5	977,750	939.73	
	3	21	6/8/09 ……… 11/2/09	726.67 …….. 140	726.67	10 × 10	459,050	1,724.68	

4.6 Summary

A new model of construction logistics planning was developed to enable the integration and optimization of the critical planning decisions of material procurement and material storage on construction sites. The procurement decision variables in the developed model are designed to identify the fixed-ordering-periods of each material in every construction stage in order to consider the changing demand rates of materials over the project duration. The dynamic layout decision variables are designed to identify the locations and orientations of material storage areas and other temporary facilities in each construction stage to dynamically consider the dynamic site space needs. The present model utilizes Genetic Algorithms to generate optimal material procurement and layout decisions in order to minimize construction logistics costs that include: material ordering, financing, stock-out, and layout costs. An application example was analyzed to demonstrate the capabilities of the present CLP model in integrating and optimizing procurement and layout decisions while considering their mutual interdependencies. The results of this analysis also illustrate that the material procurement decisions are affected by the criticality of construction activities consuming the material and site space availability, while the dynamic site layout decisions are affected by the material procurement decisions and material storage space needs as well as other site layout constraints.

CHAPTER 5
CONGESTED CONSTRUCTION LOGISTICS PLANNING MODEL

5.1 Introduction

The objective of this chapter is to present the development of a new multi-objective optimization model for congested construction logistics planning (C2LP) that is capable of modeling and utilizing interior spaces of buildings under construction to generate optimal logistics plans on congested construction sites. As shown in Figure 5.1, existing models of site layout planning and material procurement do not consider and utilize available interior spaces to accommodate long-term procurement storage areas as well as temporary facilities. This limitation causes serious problems in congested construction sites such as the inefficient utilization of available interior spaces, crowded site-level space, and costly material procurement plans because of the Just-In-Time (JIT) deliveries with underutilized trucks and increased risks of material shortage.

The proposed C2LP model is formulated and developed to help contractors and planners in generating optimal material procurement plans, interior material storage plans, exterior site layout plans, and scheduling of noncritical construction activities for congested construction sites. The model is implemented using a multi-objective Genetic Algorithms in order to generate a set of optimal site layout solutions that provide optimal tradeoffs between minimizing total construction logistics costs and minimizing project schedule criticality. The model is developed in two main phases: development and implementation phases, as shown in Figure 5.1. First, the development phase focuses on the construction site spatio-temporal representation that involves the formulation of site interior and exterior spaces as well as the relationships between construction activities and site space availability and demand. Second, the implementation phase consists of three main modules: input and data processing module, Genetic Algorithms optimization module, and logistics planning module, as shown in Figure 5.1. The following sections describe in more detail these two main development phases and the analysis of an application example that is used to evaluate the performance of the developed model.

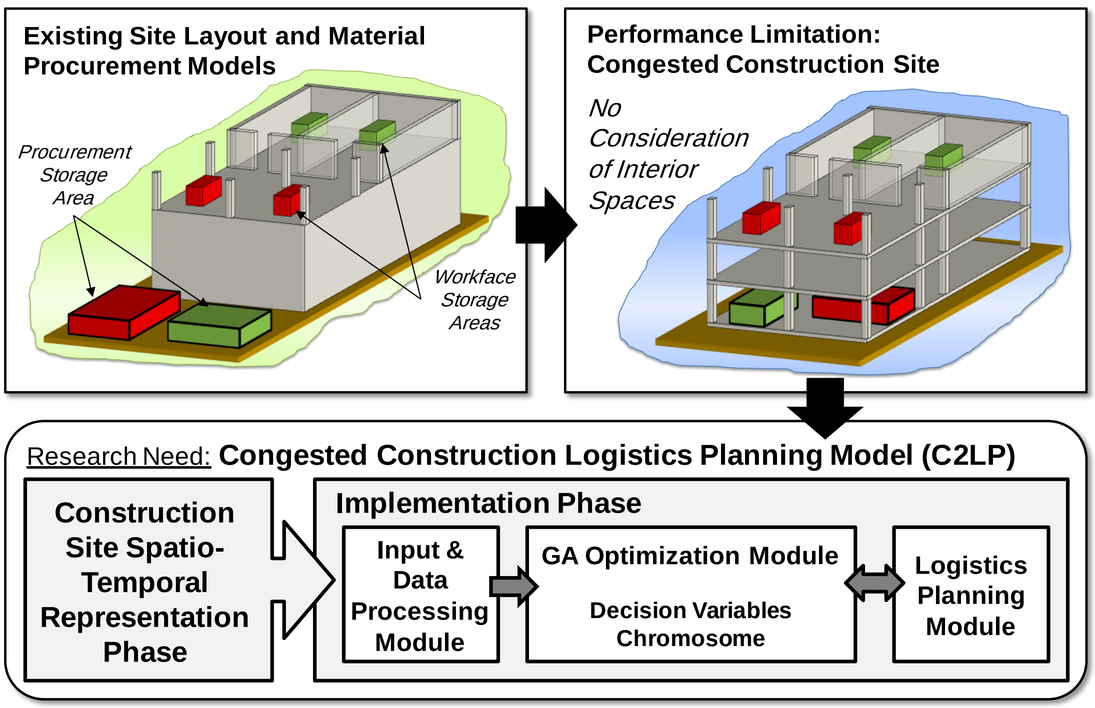


Figure 5.1 Congested Construction Logistics Planning Model

5.2 Construction Site Spatio-Temporal Representation

The present C2LP classifies construction site space under two main categories: exterior and interior spaces. First exterior space is represented as a grid of locations that is generated within the 2D rectangular boundaries of the construction site considering a fixed grid spacing that is specified by the planner, as shown in Figure 5.2. Each of these grid locations can be used to position the centroids of temporary facilities and material storage areas considering four types of layout constraints: boundary, overlap, distance, and zone constraints (see Section 3.3.3). Space demand of a temporary facility is represented as a 2D rectangle that is identified by the planner, while the dimensions of material storage areas are obtained based on material procurement plans and material footprint schedule. The layout of exterior site space is allowed to be reorganized at the end of major construction stages to generate enough spaces for new temporary facilities or material storage areas. Temporary facilities are classified into moveable and stationary facilities based on the applicability of relocating them between construction stages, as described earlier in Section 3.2.

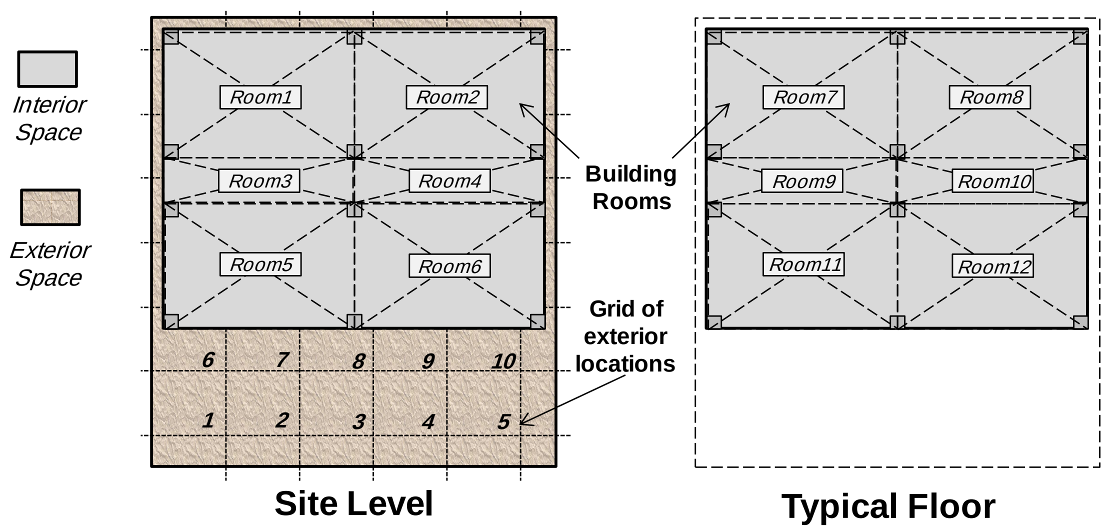


Figure 5.2 Representation of Interior and Exterior Site Spaces

Second, interior building space is broken down into a set of rooms based on the architectural design of each storey, as shown in Figure 5.3. Each room has a limited area to accommodate: (1) workspaces of interior activities to allow for the maneuver and routing of activity laborers and equipments as well as the workface (short-term) material storage areas that cover the daily demand of the activity (Thomas et al. 2005); and (2) procurement (long-term) material storage areas that cover the demand of all construction activities for an extended period of time. Construction work space demands can be represented using a set of workspaces that are distributed over different rooms of the building, as shown in Figure 5.3. The allocation of interior material storage area depends on the start of the partitioning activity (e.g. drywall construction) of the corresponding floor. If the material is delivered before the start of the floor partitioning activity, the required storage area (based on material footprint schedule) is positioned as a single storage area that can occupy a group of nearby rooms. On the other hand if the material is delivered after floor partitioning, the delivered quantity will be split over the rooms considering their spatial capacities and material footprint schedule which identifies storage area dimensions for different delivery quantities, as shown in Figure 5.3. Planners may also specify a space utilization factor (SUF) that limits room space availability for material storage areas and activity workspaces to account for irregular room shapes and needed access routes for construction crews.

Exterior and interior spaces are linked to the construction schedule in the present model in order to represent the dynamic change in space demands, availability, and constraints. First, the layout plans of site exterior space are linked to milestones in the construction schedule that represent major changes in site layout space demands and/or availability. These milestones split project duration into successive stages with different needs of temporary facilities and consumption rates of construction materials that need to be stored onsite. In addition, workspaces of exterior activities (e.g., excavation, foundation) are identified using

2D rectangular shapes or can be accommodated inside one of the defined temporary facilities (such as assembling rebar in a fabrication area).

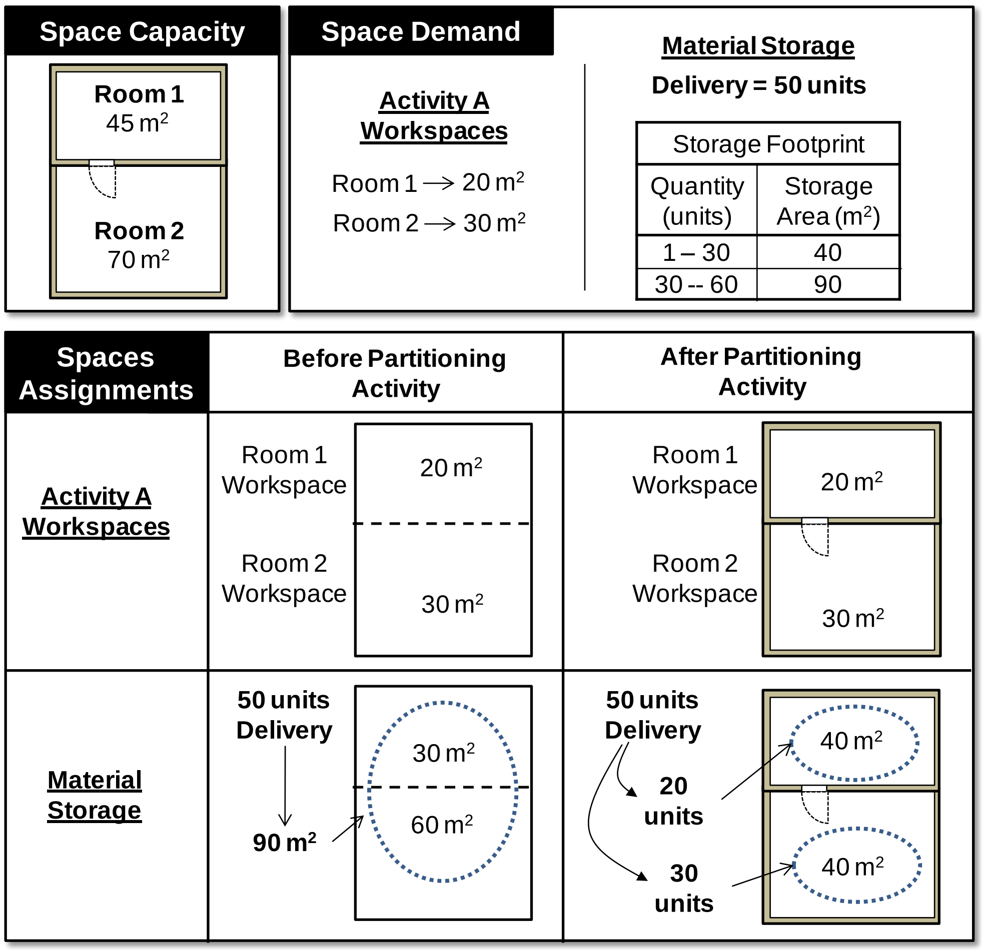


Figure 5.3 Modeling of Interior Space Capacities, Demand, and Assignments.

On the other hand, interior space rooms are linked to the construction activities using four types of relationships: workspaces, space partitioning, rooms creation, and material permissible storage periods. First, each interior activity *i* is linked to at least one room in order to identify its required area (WSA_i) for laborers, equipments, and workface material storage. Second, each room *(r)* in every building storey is linked to its partitioning activity (RPA_r) so that rooms partitioning time is considered in the interior storage of material deliveries. Third, the creation of each room is linked to one construction activity (RCA_r) (such as skeleton activities) after which this room's space can be utilized. Fourth, permissible storage periods are identified for different types of materials in order to avoid the potential negative impacts of storing materials close to the workspaces of certain activities. For example, bulk material (e.g., masonry blocks, cement, and sand) should not be stored in close proximity to finishing activities (e.g., painting) because they can degrade the quality of the finished product. Similarly, electrical fixtures cannot be stored close to rough activities (i.e. rebar fabrication) because of the high risk of fixtures damage. As such, permissible storage periods of material *m* in room *r* is identified by the scheduled finish times of permissible storage period starting and ending activities, $PSP_{m,r}^{start}$ and $PSP_{m,r}^{End}$, respectively.

5.3 Input and Data Processing Module

The objectives of this module are to: (1) gather project spatial, schedule, and logistics input data; and (2) perform analytical processing and manipulation of the gathered data in order to generate new data sets that are needed for subsequent modules. In this module, planners are required to provide the following input data: (1) project spatial data that include the dimensions of the construction site, buildings under construction, and interior building rooms (coordinates and areas); (2) project schedule data including major construction milestones/stages, list of construction activities, activities relationships, materials, and their assignment to different activities; (3) spaces creation activities; (4) activities workspaces and their area requirements; (5) partitioning activities in each floor; (6) permissible periods of interior storage for each material; (7) temporary facilities needed in each construction stage, their dimensions and travel cost rates of personnel/equipments moving between them; (8)

distance and zone constraints that are imposed due to operational and/or safety requirements for exterior material storage and temporary facilities layout; (9) suppliers data that include purchase costs, delivery costs, and average delay of their material deliveries; and (10) horizontal and vertical handling equipments/crews of all materials.

C2LP model processes and manipulates the aforementioned input data in order to identify additional useful information that is needed for the GA optimization and logistics planning modules. First, schedule input data are processed to calculate: (1) early start and finish times (ES_i and EF_i) of each activity i; (2) total floats (TF_i) of noncritical critical activities (N'); and (3) daily demand of material m (EMD_d^m) based on the activities early schedule and their material demand quantities, as shown in Equations 5.1. Second, the daily space demand (ESD_d^r) for each building room r is estimated using the activities early times and workspaces, as shown in Equation 5.2. Third, workspaces centroid (CX_i, CY_i) of each activity i is calculated using the areas of its workspaces and the locations of the corresponding rooms, as shown in Equations 5.3 through 5.5. Centroids of activities workspaces are used in the logistics planning module to calculate interior material handling costs, which is described later in Section 5.6. Fourth, the present model identifies for each room its closest neighboring rooms in the same level in order to be used to accommodate material interior storage areas.

$$EMD_d^m = \sum_{i=1}^{N} \left(\frac{AQ_i^m}{Dur_i} \times IF\{d \geq ES_i \quad AND \quad d < EF_i\} \right) \tag{5.1}$$

$$ESD_d^r = \sum_{i=1}^{N} \left(WSA_i^r \times IF\{d \geq ES_i \quad AND \quad d < EF_i\} \right) \tag{5.2}$$

$$CX_i = \left(\sum_{j=1}^{NWS_i} WSA_j^i \times WSX_i^j \right) \Bigg/ \sum_{j=1}^{NWS_i} WSA_j^i \tag{5.3}$$

$$CY_i = \left(\sum_{j=1}^{NWS_i} WSA_j^i \times WSY_i^j \right) \Bigg/ \sum_{j=1}^{NWS_i} WSA_j^i \tag{5.4}$$

$$CZ_i = \left(\sum_{j=1}^{NWS_i} WSA_j^i \times WSZ_i^j \right) \Bigg/ \sum_{j=1}^{NWS_i} WSA_j^i \tag{5.5}$$

Where,

EMD_d^m = daily demand of material *m* on day *d* based on activities early times;

N = number of construction activities;

ES_i and EF_i = early start and finish times of activity *i*;

Dur_i = duration of activity *i*;

AQ_m^i = assigned quantity of material m to activity *i*;

IF{condition} = a conditional function that returns 1 if the inside condition is satisfied, 0 otherwise.

ESD_d^r = total space demand for room *r* in day *d*;

NWS_i = number of workspaces in interior building rooms of activity *i*;

WSA_i^r = workspace area of activity *i* in building room *r*;

CX_i, CY_i, CZ_i = x, y, and z coordinates of activity *i* workspaces centroid; and

WSX_i^r, WSY_i^r, WSZ_i^r = x, y, and z coordinates of activity *i* workspace centroid in room *r*.

5.4 Genetic Algorithms Optimization Module

The objective of this module is to search for and identify optimal construction logistics plans that provide optimal tradeoffs between the two optimization objectives of minimizing logistics costs and minimizing project schedule criticality. Genetic Algorithms (GA) is utilized in the present module because of its unique capabilities in multi-objective optimization, especially in complex nonlinear problems with large search spaces (Deb et al 2001). The GA optimization module generates a set of optimal tradeoff solutions for congested logistics planning problem in three main steps, as shown in Figure 5.4: (1) formulating the chromosome of the optimization decision variables and generating an initial population of solutions; (2) evaluating the fitness (objective functions) of each solution; and (3) generating a new population using genetic operators. Steps 2 and 3 are repeated for G generations, after which a set of Pareto optimal solutions are extracted. Each of these solutions represents a unique tradeoff between the two optimization objectives. The following subsections describe in details each of these steps.

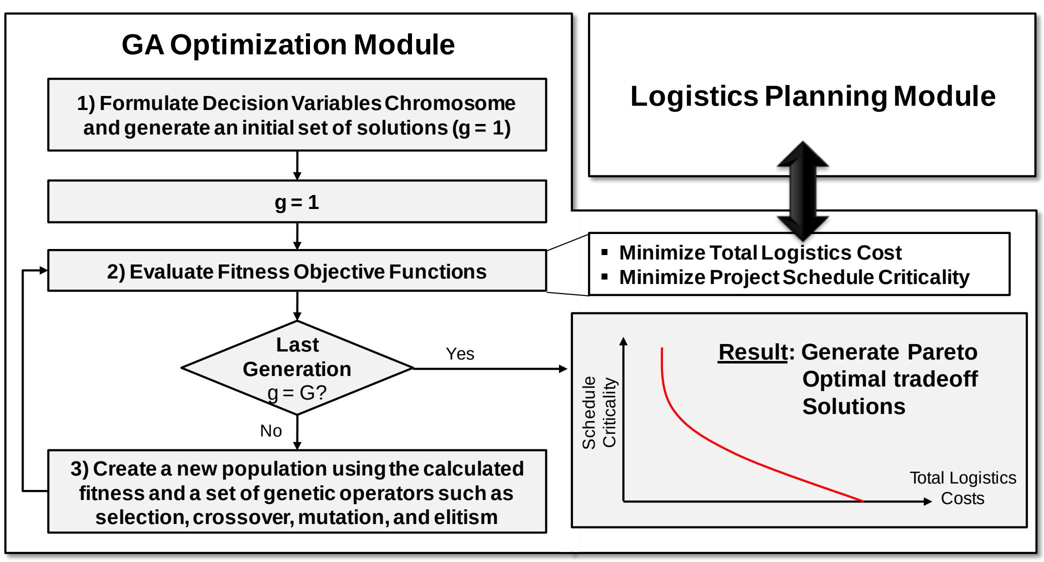


Figure 5.4 Genetic Algorithms Optimization Module

5.4.1 Decision Variables Chromosome and Initial Population Generation

The present C2LP model starts the optimization of congested construction logistics planning with formulating the decision variables chromosome and generating an initial population of solutions. A chromosome of optimization decision variables is formulated based on the input data, to represent four main categories of critical logistics decisions, as shown in Figure 5.5: (1) material procurement; (2) materials storage plan; (3) layout of temporary facilities; and (4) scheduling of noncritical activities. An initial population of solutions is generated the based on the formulated chromosome to be used the subsequent steps of the GA optimization module.

First, material procurement decision variables include Fixed-Ordering-Periods ($FOP_{m,t}$) of each material (m) in every construction stage (t), as described earlier in Section 4.2. Based on material procurement decisions, construction materials are delivered to the construction site in fixed intervals ($FOP_{m,t}$) with sufficient quantities to satisfy the demand of the construction activity scheduled in the succeeding interval period. The lower bound of each material FOP is 1 day, which represents a Just-in-Time (JIT) material procurement that is efficient in minimizing site space demands for material storage areas. Otherwise, the FOP variable can be any value greater than one representing a Just-in-Case (JIC) procurement plan with onsite material storage areas.

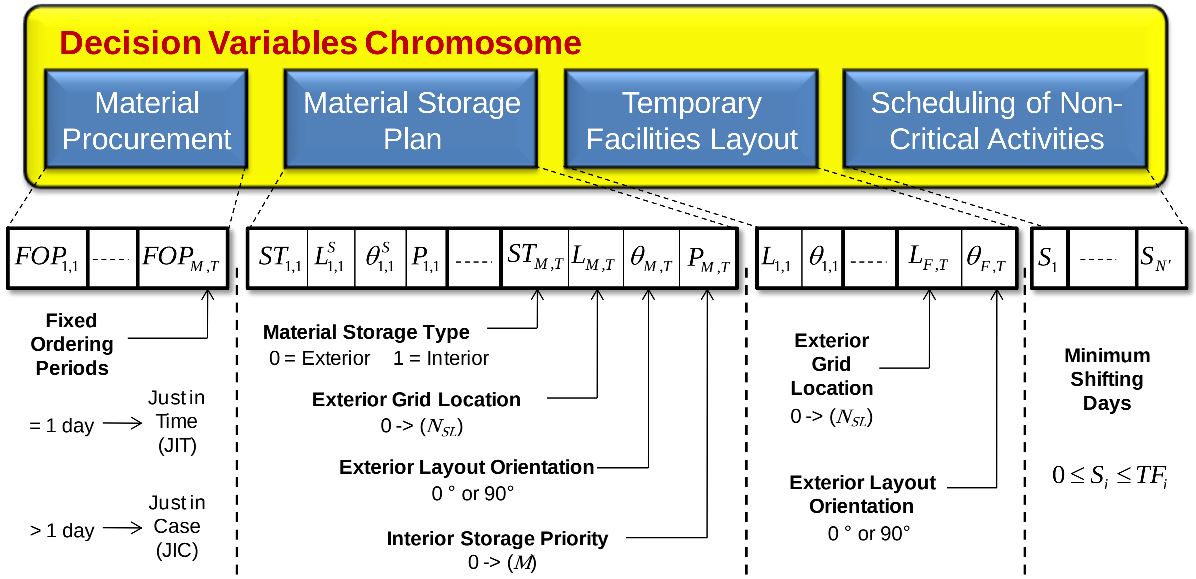


Figure 5.5 Chromosome Representation of Optimization Decision Variables

Second, materials storage decision variables are designed to specify four decisions for each material (m) in every construction stage (t): (1) material storage type; (2) location of material exterior storage area; (3) orientation of material exterior storage area; and (4) material interior storage priority. Material storage type ($ST_{m,t}$) is a binary decision variable that specifies if the delivered quantity of material m in stage t is stored in interior building rooms or in exterior space on site. If the exterior storage type is selected ($ST_{m,t}$ = 0), the second and third decision variables (exterior grid location $L^S_{m,t}$ and orientation $\theta^S_{m,t}$) are then generated to position the material storage in exterior site space. Otherwise ($ST_{m,t}$ = 1), the fourth decision variable (material interior storage priority $P_{m,t}$) is used to allocate interior building rooms to each delivery of material m in stage t using a newly developed algorithm that is described later in Section 5.5.

Third, the exterior site layout of temporary facilities is planned based on the decision variables of exterior grid location ($L_{f,t}$) and orientation ($\theta_{f,t}$) decision variables for: (1) every moveable facility in each stage during which the facility exists on site; and (2) every new stationary facility in each construction stage. The C2LP model also considers site exterior layout constraints and space availability in optimally positioning temporary facilities as well as all material storage areas which are selected to be positioned in exterior space ($ST_{m,t} = 0$).

Fourth, the scheduling of noncritical activities is defined by the number of minimum-shifting-days (S_i) of each activity within its total float. Shifting of noncritical activities, beyond their early start times, allows for providing additional interior spaces for material storage areas that can lead to lower project logistics costs. This process, however, increases project schedule criticality and the risks of project delays. The present C2LP model is therefore designed to consider this critical tradeoff between minimizing construction logistics costs and project schedule criticality, as described in the following sections.

The C2LP model is designed to generate optimal decision variables that comply with all relevant constraints that are imposed by interior space availability, exterior space availability, and suppliers' capacities. First, interior space constraints are imposed the assignment of interior spaces to material storage areas. These constraints include room capacities, creation times of rooms, and permissible periods of interior material storage. Second, four types of geometric constraints are imposed on exterior material storage areas and temporary facilities: boundary, overlap, distance, and zone constraints. Third, the maximum ordering quantities of material suppliers are considered in the present model during the generation of material procurement decision variables (Fixed-Ordering-Periods *FOP*).

5.4.2 Optimization Objective Functions

The present model is designed to optimize the tradeoff between the two important planning objectives of minimizing total construction logistics costs and minimizing project schedule criticality. First, total logistics cost (*TLC*) is calculated using Equation 5.7 as the summation of: (1) ordering cost; (2) financing cost ; (3) stock-out cost; and (4) site layout cost. Ordering cost (*OC*) represents the purchase of the needed materials from the supplier and their delivery costs to the construction site. Financing cost (*FC*) represents the lost interest on the contractor's capital that is tied up in onsite material inventories that are created based on material procurement decisions. Stock-out cost (*SC*) includes any project delay costs that occur as a result of late material deliveries. Layout cost (*LC*) includes the travel cost of contractor's personnel/equipments moving between site facilities, cost of material handling time from interior and/or exterior storage areas to activities workspaces, and cost of reorganizing the site layout between construction stages, if applicable. Each of these costs is calculated in the logistics planning module considering the generated values of the optimization decision variables, as described later in Section 5.5.

$$CLC = OC + FC + SC + LC \tag{5.7}$$

$$LC = MHCI + MHCE + RTC + SRC \tag{5.8}$$

Where,

CLC = construction logistics costs;

OC = ordering cost;

FC = financing cost;

SC = stock-out cost;

LC = layout cost;

LC = layout cost;

$MHCI$ = material handling cost of interior storage areas:

$MHCE$ = material handling cost of exterior storage areas:

RTC = resource traveling cost; and

SRC = site reorganization cost.

The schedule criticality is calculated in the C2LP using a newly developed metric that aggregates the amount of consumed floats of noncritical activities as a result of their scheduling decision variables. As shown in Equation 5.9, a criticality index (CI_i) is calculated for each activity i as the ratio between: (1) the number of days that activity i is shifted within its total float, as the difference between its scheduled start (SS_i) and early start (ES_i) times; and (2) the total float (TF_i) of activity i. The scheduled times of noncritical activities are calculated using a new scheduling algorithm in the logistics planning module, which is described later in Section 5.5. The calculated criticality indexes of all noncritical activities are then averaged to calculate the project schedule criticality index (SCI), as shown in Equation 5.9. The lower bound of the activity criticality index (CI_i) is 0, which represents scheduling the activity on its early start time ($SS_i = ES_i$); while the upper bound is 1, which represents scheduling the activity on its late start time ($SS_i = LS_i$). Accordingly, the schedule criticality index (SCI) of the whole project ranges from 0 (all activities are scheduled on their early times) to 1 (all activities are scheduled on their late times).

$$SCI = \frac{1}{N'} \times \sum_{i=1}^{N'} CI_i = \frac{1}{N'} \times \sum_{i=1}^{N'} \left(\frac{SS_i - ES_i}{TF_i} \right) \tag{5.9}$$

where

SCI = Schedule criticality index;

N' = number of noncritical activities;

CI_i = criticality index of activity i;

SS_i = scheduled start time of activity i;

ES_i = early start time of activity i; and

TF_i = Total float of activity i.

5.4.3 Generation of New Populations

A new population of solutions is created in every generation based on the calculated fitness values (objective functions) using a set of genetic operators such as selection, crossover, mutation and elitism. The present optimization module utilizes a multi-objective optimization algorithm named Non-dominated Sorted Genetic Algorithm II (NSGAII) (Deb et al. 2001) due to its unique capabilities in: (1) generating, in a single run, a set of optimal pareto solutions with different tradeoffs between the conflicting optimization objectives; and (2) utilizing novel metrics, such as elitism and pareto front crowding, in order generate a wide and uniform spectrum of high quality tradeoff solutions (Deb et al. 2001, El-Rayes and Kandil 2005). The set of optimal tradeoff solutions of congested construction logistics plans are extracted after the last generation and planners can select a single solution that fits the specific needs and priorities of each project.

5.5 Logistics Planning Module

The logistics planning module is designed to calculate construction logistics costs and schedule criticality index for each solution (i.e., decision variables chromosome) in all GA populations. The logistics planning module is performed in four main steps, as shown in Figure 5.6: (1) scheduling noncritical activities using the generated values of noncritical activities minimum-shifting-days and calculating the resulting schedule criticality index; (2) generating material procurement plans based on updated material demand profiles of shifted construction schedule and procurement decision variables to calculate ordering, financing, and stock-out costs; (3) calculating exterior layout costs that include material exterior handling, resources travel, and site reorganization costs based on the decision variables of temporary facilities layout and material storage plan; and (4) assigning interior rooms to material storage areas based on material storage type and priority decision variables.

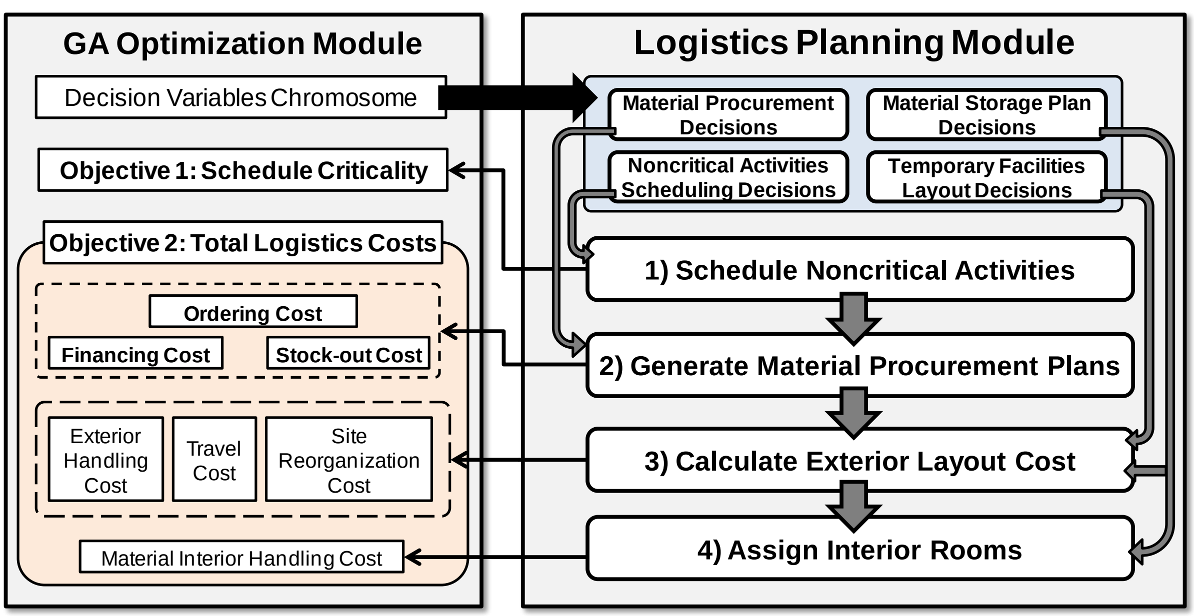


Figure 5.6 Logistics Planning Module and its Interaction with GA Optimization Module

5.5.1 Scheduling Noncritical activities

The scheduled start and finish times of noncritical activities are calculated in this step based on the generated scheduling decision variables and considering the cascading effect of shifting early activities on later ones. A new forward-path scheduling algorithm was developed to calculate scheduled times of every noncritical activity in ten main steps, as shown in Figure 5.7:

Step 1: Initialize the schedule times of noncritical activities to their early times and mark all of them as not shifted ($Shifted_i = False$).

Step 2: Select the earliest noncritical activity that satisfies the following two conditions: (1) it was not shifted in previous cycles of the algorithm; and (2) all of its predecessors are shifted.

Step 3: Calculate existing-shifting-days (S_i^E) of the selected activity that occurred as a result of shifting earlier activities in previous cycles of the algorithm.

Step 4: Calculate remaining-shifting-days (S_i^R) as the nonnegative difference between the generated minimum-shifting-days (decision variables S_i) and existing-shifting-days (S_i^E) of the selected activity.

Step 5: Adjust the scheduled start and finish times of the selected activity considering the remaining-shifting-days (S_i^R) that was calculated in step 4.

Step 6: Adjust the scheduled start and finish times of all succeeding activities till the last activity of project network based on the scheduled times of the selected activity that were calculated in step 5.

<u>Step 7:</u> Repeat steps 2 through 6 for all noncritical activities in the project network. After scheduling all noncritical activities, steps 8 and 9 and performed.

<u>Step 8:</u> Calculate schedule criticality index (SCI) using Equation 5.9 based on the scheduled and early times of all noncritical activities. This value is passed to the GA optimization module to be considered as one of the two optimization objectives in the selection of the solutions for the next generations.

<u>Step 9:</u> Generate demand profiles of construction materials and room spaces based on activities scheduled times (SMD_d^m and SSD_d^r) by updating the early times profiles (EMD_d^m and ESD_d^r) to reflect shifting of noncritical activities. Furthermore, the cumulative materials demand profiles (SCD_d^m) are calculated using the daily materials demand profiles of activities scheduled times (SMD_d^m).

<u>Step 10:</u> Calculate the number of violations to room capacity constraints as a result of simultaneously scheduling noncritical activities in the same room with workspace demand higher than room's capacity. Any violation to room space capacities is reported to the GA optimization module to be considered during the selection of the solutions that will survive in the future generations.

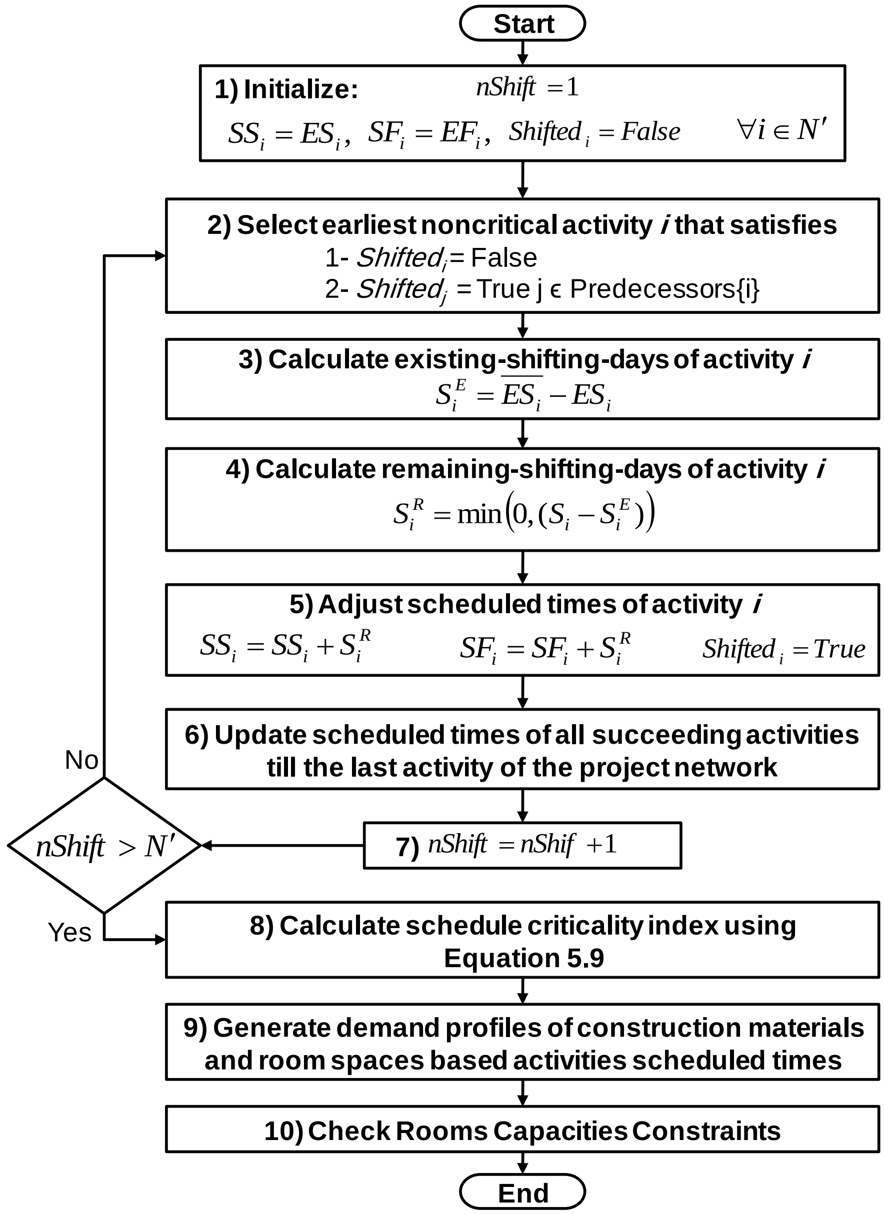


Figure 5.7 Noncritical Activities Scheduling Algorithm

The performance of noncritical activities scheduling algorithm is illustrated using a small example, as shown in Figure 5.8, which represents a project network of two critical activities (D and E) and three noncritical activities (A, B, and C). The GA generated values of the minimum-shifting-days of noncritical activities A, B, and C are 2, 3, and 2, respectively. Activities B and E require workspaces of 30 m^2 and 20 m^2, respectively in a building interior room R1 which has a capacity of 50 m^2. The noncritical activities are scheduled using the developed algorithm in three cycles. In the first cycle, activity A is selected as the earliest noncritical activity that was not shifted in previous cycles and has no predecessors. The remaining-shifting-days of A is calculated to be 2 which is the difference between its minimum-shifting-days (2 days) and its existing-shifting-days (0 days). Accordingly, activity A is shifted 2 days and all succeeding activities are rescheduled accordingly. In the second cycle, activity B is selected to be shifted by 1 day ($S_B^R = 1$) which is the difference between its minimum-shifting-days (3 days) and its existing-shifting-days (2 days). In the third cycle, activity C will not be shifted since its remaining-shifting-days is equal to zero ($S_C^R = 0$) because its existing-shifting-days due to the shift of its predecessors (3 days) is greater than its minimum-shifting-days (2 days).

After scheduling all noncritical activities, the demand profile of room R1 space is updated based on the aforementioned scheduling of the noncritical activities. As shown in Figure 5.8, the present model detects a constraint violation on days 10 and 11 because non critical activity B is scheduled on these days simultaneously with critical activity E, which results in a total space demand of 50 m^2, exceeding the capacity of room R1. These violations are considered by the GA Optimization Module in the selection and evolution of the analyzed solutions for future generations. As such, the present model is designed to generate optimal noncritical scheduling decisions that minimize material logistics costs while complying with room space capacities.

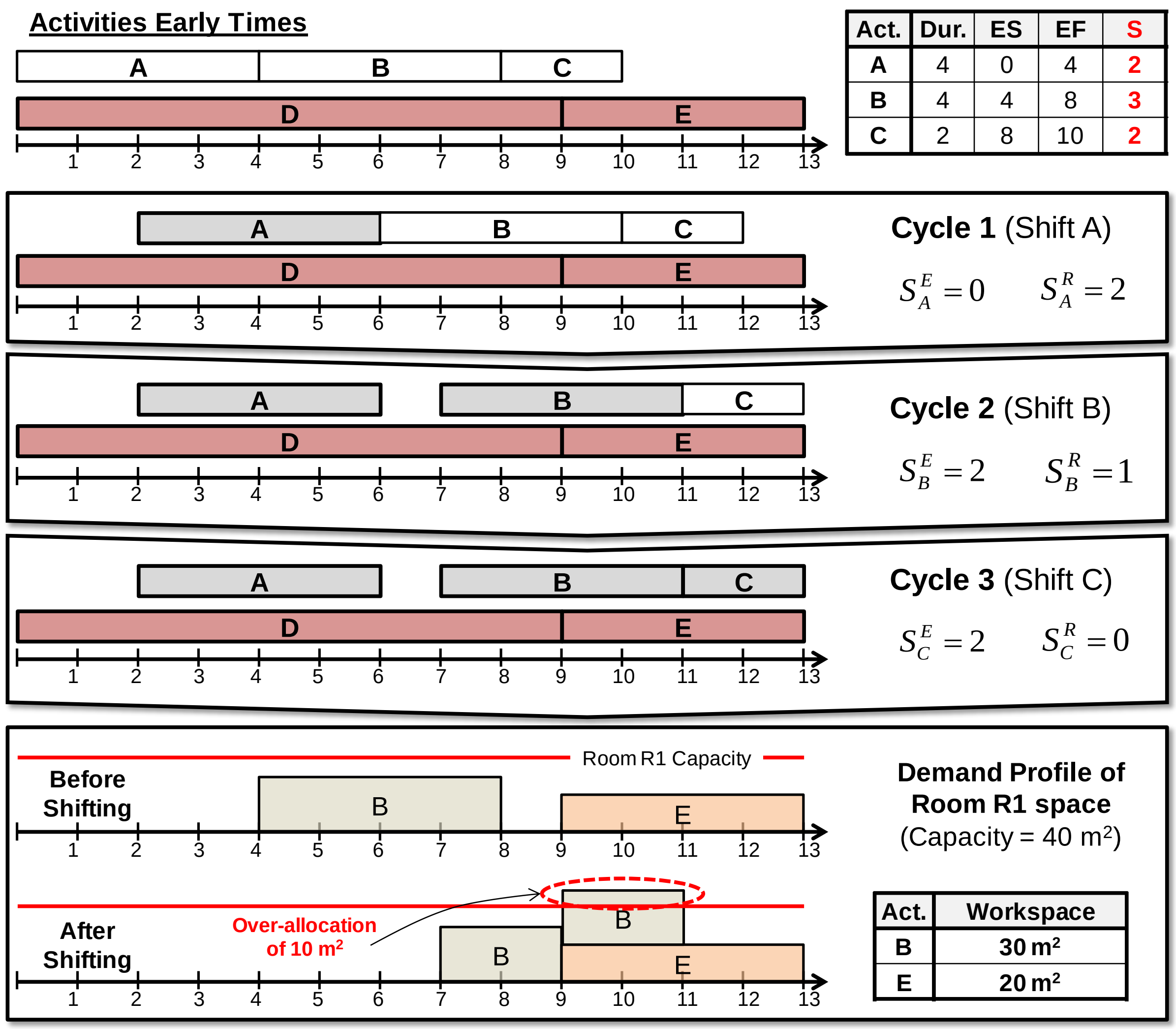


Figure 5.8 Example of Scheduling Noncritical Activities in the Present C2LP Model

5.5.2 Generation of Material Procurement Plans

Material procurement plans are generated using the procurement decision variables passed from the GA optimization module in order to identify the times and quantities of material deliveries in each construction stage. A Fixed-Ordering-Period system is adopted in the current model to represent the supply of construction materials in ordering cycles of fixed intervals ($FOP_{m,t}$); where material quantities are delivered at the beginning of each cycle to satisfy construction site demand until the delivery of the next cycle. The procurement plans are generated in the present model using a novel computational algorithm, as shown in Figure 5.9, in nine main steps:

<u>Step 1:</u> Set start day of the first ordering cycle of material *m* to be the first day of stage *t*, and its finish day to be after the Fixed-Ordering-Period $FOP_{m,t}$ (procurement decision variable) that is generated by the GA module.

<u>Step 2:</u> Calculate needed material quantity during the cycle as the difference between the cumulative demands (based on scheduled activities times) of material *m* at the end and start of the ordering cycle, SCD_{d2}^{m} and SCD_{d1}^{m} , respectively. If this calculated quantity is bigger than 0, go to next step; otherwise go to step 6.

<u>Step 3:</u> Record the delivery of the current cycle of the procurement plan of material *m* in stage *t* by incrementing the number of material orders (NOR_{m}^{t}) and storing its delivery quantity ($Q_{NOR}^{m,t}$) that is calculated in the previous step.

<u>Step 4:</u> Calculate the maximum delivery quantity of material *m* in stage *t* ($Q_{MAX}^{m,t}$) as the maximum of the quantity values that were calculated in previous ordering cycles ($Q_{NOR}^{m,t}$). The maximum delivery quantity is essential for calculating exterior material storage areas using material footprint schedule.

<u>Step 5:</u> If interior storage type is selected for material *m* in stage *t* ($ST_{m,t}$ = 1), this step records the delivery of the current ordering cycle in Interior Storage Log of the delivery day (*d1*). Indoor Storage Log identifies all materials deliveries in each day that need to be stored in interior building rooms.

Step 6: Set (1) start day of the next ordering cycle as the finish day of current cycle; and (2) finish day of the next cycle as the earliest of the finish day of the current cycle and the finish day of stage *t* ($StageF_t$);

Step 7: Repeat steps 2 through 6 for material *m* for all next ordering cycles in stage *t*. If all ordering cycles in stage *t* are performed, generate the procurement plan of material *m* in next cycle by increment stages counter ($t = t + 1$) can go to step 1.

Step 8: Repeat steps 1 through 6 for other materials to generate their procurement plans in every construction stage. Terminate the algorithm after all materials are considered.

Step 9: Calculate ordering, financing and stock-out costs based on the generated procurement plans from the previous step. The calculations of these logistics cost are described in more detail in Section 4.4.

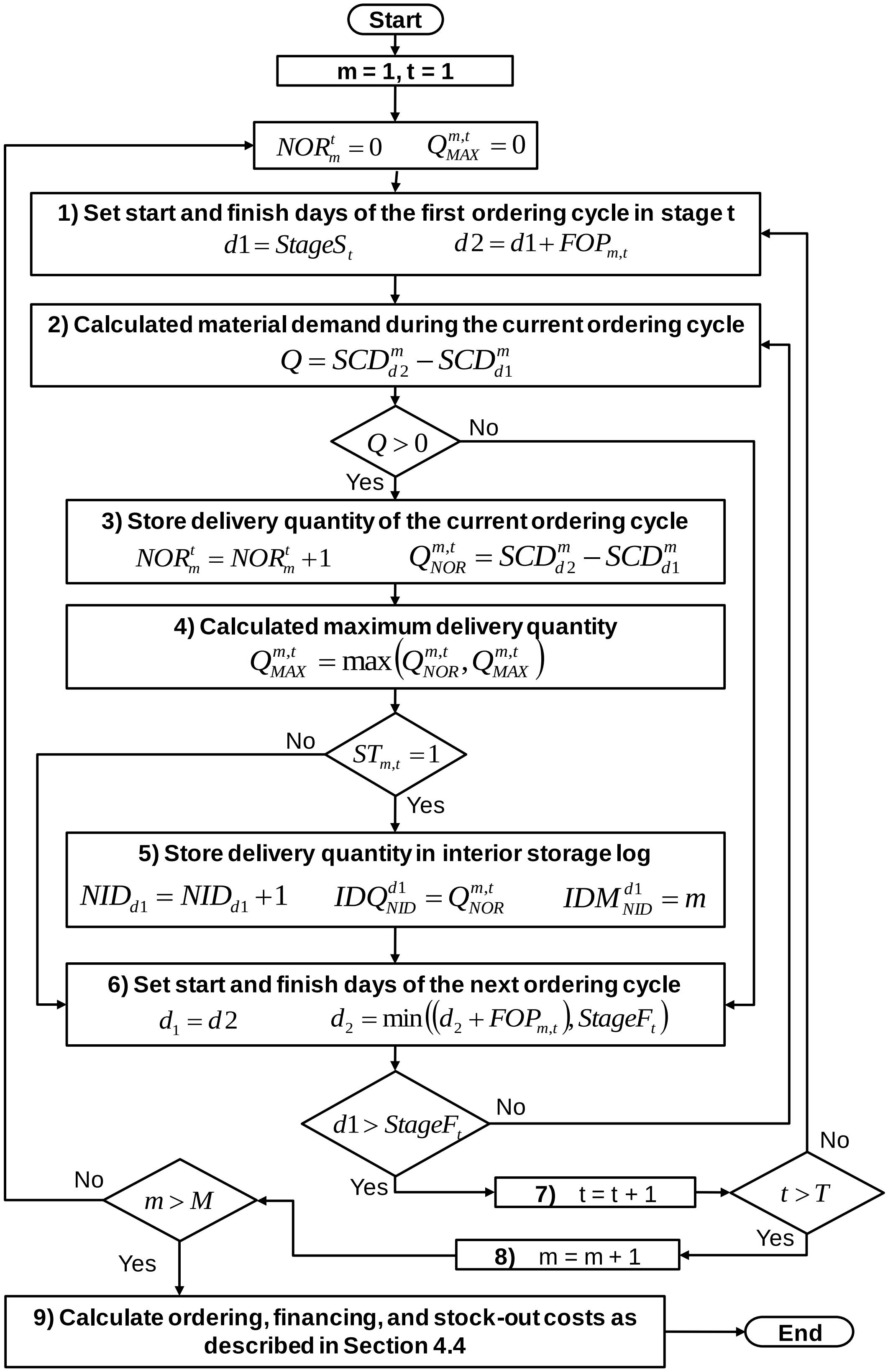


Figure 5.9 Material Procurement Plans Generation Algorithm

5.5.3 Calculation of Exterior Site Layout Cost

The logistics planning module is designed to calculate the travel cost of onsite contractor resources (*RTC*), site reorganization cost (*SRC*), and material exterior handling cost (*MHCE*) using the generated decision variables of the temporary facilities layout and material storage plan. First, the travel cost is calculated for onsite personnel, laborers, and equipments moving between: (1) every pair of temporary facilities, such as the travel of laborers from a fabrication area to the site toilets; and (2) buildings under construction and temporary facilities, such as moving construction waste from activities workspaces to waste disposal bin, as shown in Figure 5.10. Resource travel cost is calculated using Equation 5.10 that considers: (1) Euclidian travel distances based the generated locations and orientations of each temporary facility ($L_{f,t}$ and $\theta_{f,t}$) and material storage area ($L^{S}_{m,t}$ and $\theta^{S}_{m,t}$); and (2) travel cost rates of each traveling link.. Second, the site reorganization cost is calculated using Equation 5.11 for every moveable facility if its location or orientation is changed between successive construction stages.

$$RTC = \sum_{t=1}^{T} \sum_{f=1}^{NF_t - 1} \sum_{g=f+1}^{NF_t} C^{t}_{f,g} \times D^{t}_{f,g} + \sum_{t=1}^{T} \sum_{f=1}^{NF_t} \sum_{g=1}^{B_t} C^{t}_{f,g} \times D^{t}_{f,g} \tag{5.10}$$

$$SRC = \sum_{t=1}^{T} \sum_{f=1}^{NF_t^M} E_f \times RC_f \times IF\left\{D_f^{t,t-1} > 0 \quad OR \quad \theta_f^t \neq \theta_f^{t-1}\right\} \tag{5.11}$$

Where

RTC = total resource traveling cost;

T = number of project stages;

M = number of project materials;

NF_t = number of temporary facilities used in stage t;

NB_t = number of buildings under construction in stage t;

$C^t_{f,g}$ = travel cost rate of resources between facilities f and g in stage t;

$D^t_{f,g}$ = Euclidian distance between facilities f and g in stage t;

SRC = site reorganization cost;

$D^{t,t-1}_f$ = Euclidian distance between facility f's positions in stages t and t-1;

E_f = facilities existence factor equals to 1 if the moveable facility f exists in previous stage t-1, and 0 otherwise; and

RC_f = relocation cost of moveable facility f; θ^t_f = orientation angle of facility f in stage t.

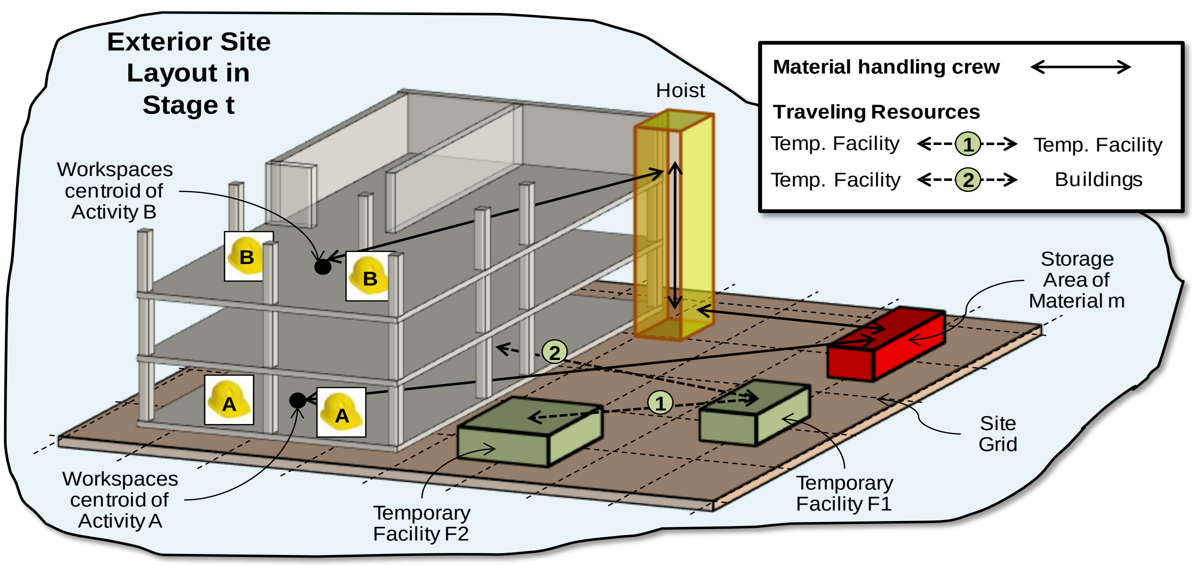


Figure 5.10 Distances of Material Handling and Traveling Resources

Third, the material exterior handling cost is calculated using Equation 5.12 through 5.15 for laborers and crews moving materials from exterior storage areas to workspaces of demanding activities. As shown in Figure 5.10, the calculation of exterior handling cost between the exterior storage area of material *m* and the location of activity *i* ($MHCE^{t}_{m,i}$) depends on the elevation of workspaces centroid relative to site elevation where the storage area reside. The material is handled directly to a demanding construction activity (see activity A in Figure 5.10) if its workspace centroid is in the same elevation of the exterior site level. This occurs if the activity is either performed in the first floor or it is an exterior activity. Otherwise, handling crews move the needed material in three steps (see activity B in Figure 5.10): (1) horizontal movement from material exterior storage area to the location of material hoist or lift; (2) vertical movement from site level to activity's level; and (3) from the location of material hoist to activity's workspaces centroid. It should be noted that Equations 5.12 through 5.15 apply only for materials with exterior storage type (decision variables $ST_{m,t}$ = 0). Handling costs of interior material storage areas ($ST_{m,t}$ = 1) are calculated in the next section that describes the last step of the logistics planning module.

$$MHCE = \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{i=1}^{N}\left(1 - ST_{m,t}\right) \times MHCE^{t}_{m,i} \tag{5.12}$$

$$MHCE^{t}_{m,i} = \begin{cases} C^{t}_{m,i} \times D^{t}_{m,i} & \overline{D}^{t}_{m,i} = 0 \\ C^{t}_{m,i} \times D^{t}_{m,H} + \overline{C}^{t}_{m,i} \times \overline{D}^{t}_{m,i} + C^{t}_{m,i} \times D^{t}_{H,i} & otherwise \end{cases} \tag{5.13}$$

$$C^{t}_{m,i} = \frac{2 \times (Q^{t}_{m,i} / q_{cr}) \times HCR_{cr}}{v_{cr}} \tag{5.14}$$

$$\overline{C}^{t}_{m,i} = \frac{2 \times (Q^{t}_{m,i} / q_{H}) \times HCR_{H}}{v_{H}} \tag{5.15}$$

Where,

MHCE = total exterior material handling cost;

$MHCE_{m,i}^{t}$ = exterior handling cost of material m in stage to activity i;

$C_{m,i}^{t}$, $\overline{C}_{m,i}^{t}$ = travel cost rate of handling crew and vertical hoist transporting material m from its exterior storage area in stage t to activity i ;

$D_{m,i}^{t}$, $\overline{D}_{m,i}^{t}$ = horizontal and vertical distances between material m storage area and activity i workspaces centroid in stage t;

$D_{m,H}^{t}$ = horizontal distance between material m storage area and material vertical hoist in stage t;

$Q_{m,f}^{t}$ = quantity of activity i demand for material m in stage t, calculated based on scheduled times of activity i;

HCR_{cr} , HCR_{H} = hourly cost rate of handling crew c*r* and material vertical hoist ($/hour);

q_{cr} , q_{H} = handling capacities of handling crew c*r* and material vertical hoist; and

v_{cr} , v_{H} = speed of handling crew c*r* and material vertical hoist (m/hour).

5.5.4 Assignment of Interior Room Spaces to Material Storage Areas

Interior material storage areas are positioned in building rooms that provide the lowest interior material handling cost while complying with imposed interior space constraints. A newly developed Interior Storage Space Assignment (ISSA) algorithm is developed in the present model to store every material delivery in each day of the project, as shown in Figure 5.11. The ISSA algorithm interacts with two other algorithms: Interior Space Constraints

Checking (ISCC) and Interior Handling Cost Calculation (IHCC), which are described later in this section. The ISSA algorithm assigns spaces of building rooms to interior material storage areas in 10 main steps:

Step 1: Reorder material deliveries stored in the Interior Storage Log of day *d* based on the GA generated values of material priorities decision variables ($P_{m,t}$), starting with the highest priority value.

Step 2: Retrieve material index (*m*) and quantity (*DQ*) of delivery *j* of the Interior Storage Log of day *d* to be positioned in a building room.

Step 3: Calculate the number of constraints violations (*nV*) that are committed for the storage of material *m* delivery on day *d* in room *r* and its neighboring rooms (if needed) using the Interior Space Constraints Checking (ISCC) algorithm. The ISCC algorithm is designed to identify and report the number of violated constraints of room space capacities, room creation time, and permissible storage periods. A detailed description of the ISCC algorithm is presented later in this section.

Step 4: Calculate the cost of material *m* handling (*hCost*) from its storage area in room *r* to its demanding activities workspaces using the Interior Handling Cost Calculation (IHCC) algorithm, which is explained in detail later in this section.

Step 5: Select room *r* for the storage of material *m* delivery in day *d* if it provides the lowest handling cost and the lowest number of constraints violations.

Step 6: Repeat Steps 3 through 5 for all building rooms to examine the feasibility of utilizing each room to accommodate the storage of delivery *j*, calculate the resulting interior handling cost, and select the best room with the lowest handling cost and constraints violation.

Step 7: Add the interior handling cost of the selected room to the total interior material handling cost (MHCI) of the project and add the number of constraints violations of the selected room (nV_{min}) to the total number of interior space constraints violation on day d (nV_d).

Step 8: Update the space demand profile (SSD_d^r) of the selected room r and its neighboring rooms that are used to store DQ units of material m on day d. Updated space demand profiles are used to check the possibility of storing next material deliveries that need interior storage spaces.

Step 9: Repeat Steps 2 through 8 for the storage of remaining material deliveries in day d. If all day d deliveries are stored in building rooms, go to step 10.

Step 10: Repeat Steps 1 through 9 for the interior storage of all material deliveries in succeeding project working days. If all project days are analyzed until its finish date, report the total interior material handling cost (*MHCI*) and the number of interior space constraints violations of every day d (nV_d) to the GA optimization module to be considered for the selection of the considered solution for the evolution of next generations.

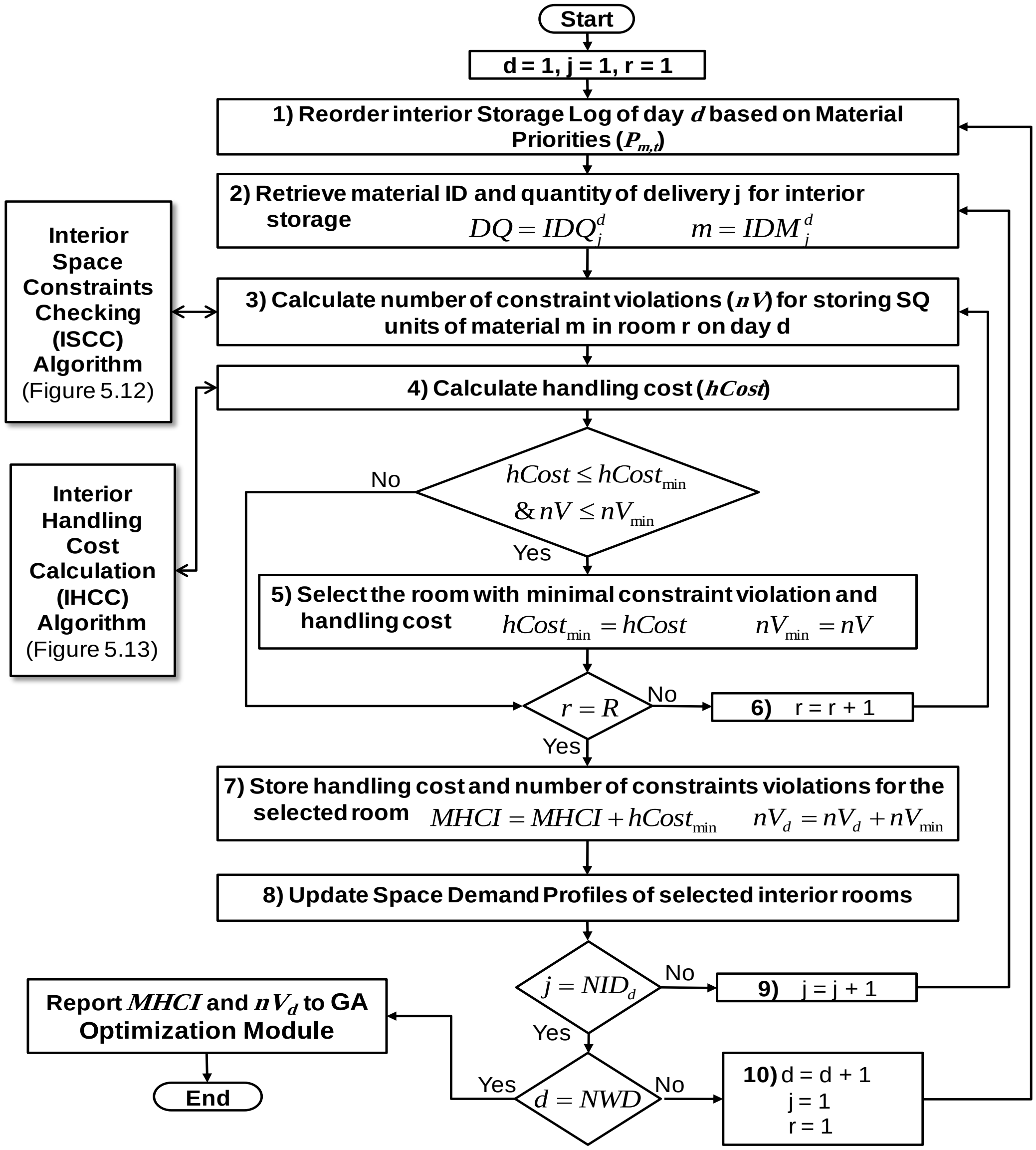


Figure 5.11 Interior Storage Space Assignment (ISSA) Algorithm

Interior Space Constraints Checking (ISCC) Algorithm

The objective of the Interior Space Constraints Checking (ISCC) algorithm is to evaluate the feasibility of positioning a material storage area in building rooms and report any violations of room space capacities, room creation, and/or permissible storage period constraints, as shown in Figure 5.12. The ISCC algorithm computes the number of violations (*nV*) for these three interior space constraints by performing the following 7 steps:

Step 1: The ISCC algorithm interacts with Interior Storage Space Assignment (ISSA) algorithm, described previously, by acquiring the following input: material index (m), room index (r), quantity of material delivery to be stored (DQ), and delivery day d.

Step 2: Set the start and finish times of the current delivery storage period considering current day d, fixed-ordering-period ($FOP_{m,t}$), and current stage finish time ($StageF_t$).

Step 3: Retrieve the scheduled partitioning time of room r by: (1) acquiring the index of its partition activity (RPA_r); and (2) setting its partitioning time (RPD_r) as the scheduled start of activity RPA_r. If the current day d is before the calculated partitioning time, go to step 4, otherwise go to step 5.

Step 4: Check the violation of room r capacity constraint for the case of storing material m delivery before room's partitioning time as a single storage area that occupies the space of room r and its neighboring rooms in the same floor, if needed. Room capacity violation is identified by: (a) calculating available space (SA_{av}) of room r considering its capacity ($Area_r$), its maximum space demand ($SSD_{d_1,d_2}^{r,MAX}$) during current delivery storage period based on scheduled times of noncritical activities, and interior space utilization factors (SUF) defined by the planner; (b) computing required storage area (SA_{req}) of delivery quantity (DQ) using material m footprint schedule; (c) calculating the remaining part (SA_{rem}) of the storage area that cannot be positioned in room r and need to be positioned in neighboring rooms, and go to step 6 if the whole storage area is positioned in room r; (d) looping over all neighboring rooms (start with closest rooms) to position the remaining part of the storage area similar to steps 4-a through 4-c; and (e) recording a violation if there is still part of the storage area that cannot not be positioned in room r and its neighboring rooms in the same floor.

Step 5: Check the violation of room *r* capacity constraint for the case of storing the material delivery after room's partitioning time as independent storage areas in room *r* and it neighboring rooms, if needed. Room capacity violation is identified by: (a) calculating available space (SA_{av}) of room *r* similar to step 4-a and the corresponding possible storage quantity (SQ_{pos}) based on material *m* footprint schedule and dimensions of both room *r* and identified storage area; (b) calculating remaining storage quantity (DQ_{rem}) that cannot be stored in room *r* and need to be stored in its neighboring rooms, and go to step 6 if the whole quantity of material *m* delivery is stored in room *r*; (c) looping over all neighboring rooms (start with closest rooms) to position the remaining quantity similar to steps 5-a and 5-b; and (e) recording a violation if there is still remaining quantity of material *m* delivery that cannot not be stored in room *r* and its neighboring rooms.

Step 6: Retrieve room *r* creation time by: (1) acquiring the index of its creating activity (RCA_r); and (2) setting its creation time (RCD_r) as the scheduled finish time of activity RCA_r. Record a violation if the start time of current delivery storage period d_1 is before the creation time of room *r*, otherwise go to step 7.

Step 7: Retrieve permissible period of storing material *m* delivery in room *r* by acquiring the indices of period starting and ending activities, $PSP_{m,r}^{Start}$ and $PSP_{m,r}^{End}$ respectively. Record a violation of material *m* storage in room *r* if either the start or finish times of the current delivery storage (d_1 or d_2) is within the material *m* permissible storage period.

Step 8: Return the number of recorded constraints violations (*nV*) to Interior Storage Space Assignment (ISSA) algorithm.

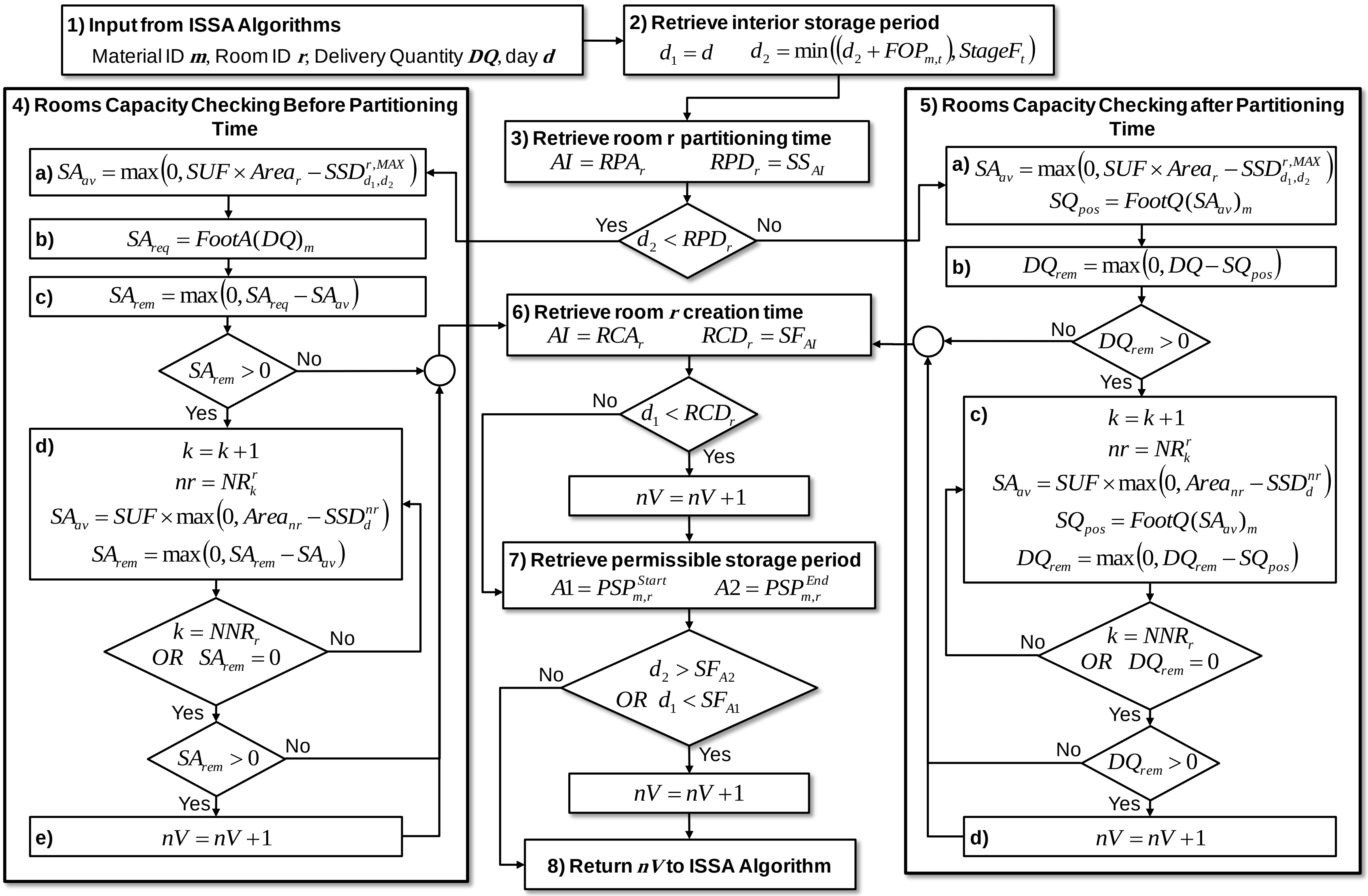


Figure 5.12 Interior Space Constraints Checking (ISCC) Algorithm

Interior Handling Cost Calculation (IHCC) algorithm

The objective of this algorithm is to calculate the cost of handling material *m* from interior storage areas of day *d* delivery to all demanding activities that are in progress until the next delivery time. As shown in Figure 5.13, the IHCC algorithm is performed in six main steps:

Step 1: Retrieve the following input data every time the IHCC algorithm is called by the ISSA algorithm: material index (*m*), room index (*r*), fixed-ordering-periods of material *m* in current stage *t* ($FOP_{m,t}$), and delivery day *d.*

Step 2: Calculate the demand period ($DP_{m,i}^{d}$) of activity *i* that needs material *m* during the interior storage period of day *d* delivery. As shown in Figure 5.14, the demand period of activity *i* is calculated based on: (1) its scheduled start and finish times (SS_i and SF_i) which depend on the generated decision variables of noncritical activities scheduling; and (2) the fixed-ordering-period of material *m* procurement during current stage *t* ($FOP_{m,t}$). As such, the demand period is identified for each activity that either starts or finishes during the storage period of the delivered quantity (i.e., from day *d* till day $d + FOP_{m,t}$).

Step 3: Calculate the demand quantity of activity *i* ($DQ_{m,i}^{d}$) as the portion of the activity's total demand ($Q_{m,i}$) that is needed during the corresponding demand period ($DP_{m,i}^{d}$), assuming a uniform material consumption rate over the activity's duration.

Step 4: Calculate the cost ($MHCI_{m,i}^{d}$) of handling $DQ_{m,i}^{d}$ quantity of material *m* from the centroid of delivery *d* storage area(s) to workspaces centroid of activity *i*. The $MHCI_{m,i}^{d}$ cost is calculated using Equations 5.16 through 5.18 considering: (1) the vertical distance between activity *i* workspaces centroid and centroid of material *m* storage area(s) in room *r* and neighboring rooms; (2) the horizontal distances between activity's workspaces, material *m* storage area(s), and material hoist; and (3) the travel cost rates of handling crews/laborers and material hoist that depend on their handling capacities, hourly cost, and handling speed. Activity *i* handling cost ($MHCI_{m,i}^{d}$) is then added to the total interior handling cost (*hCost*) that was calculated for previously analyzed activities.

<u>Step 5:</u> Repeat Steps 2 through 4 to calculate material *m* handling costs to all activities.

<u>Step 6:</u> Return the total interior handling cost (*hCost*) for material *m* storage in room *r* on day *d* to the ISSA algorithm.

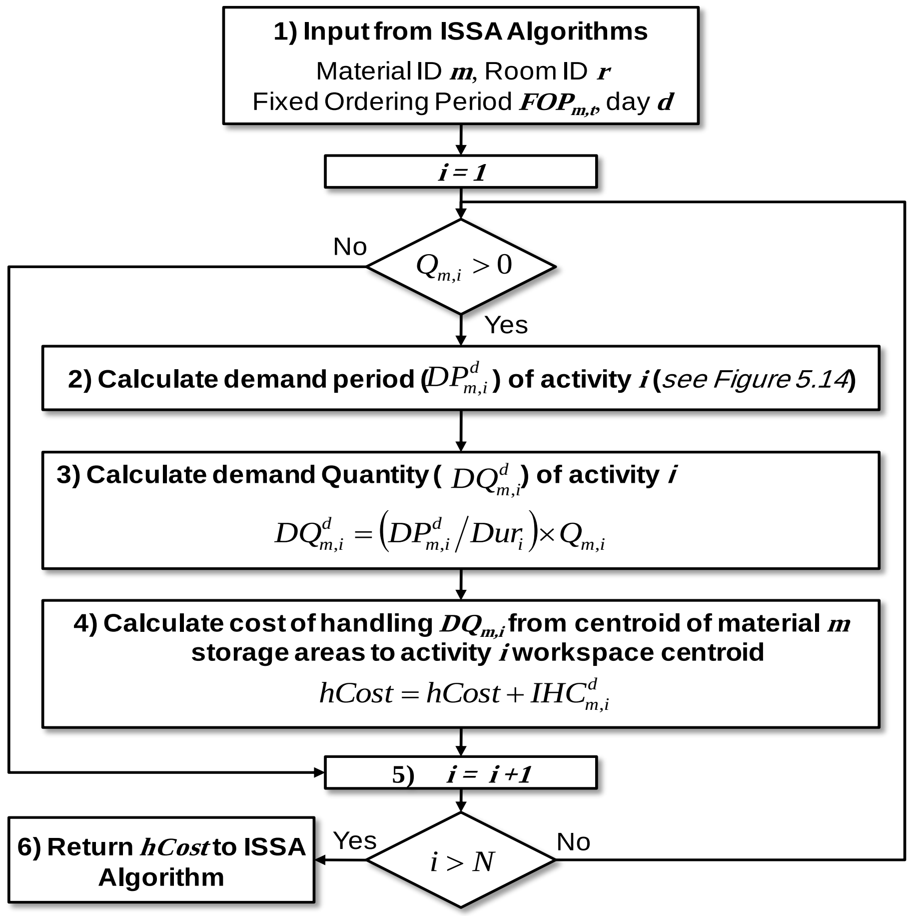


Figure 5.13 Interior Handling Cost Calculation (IHCC) Algorithm

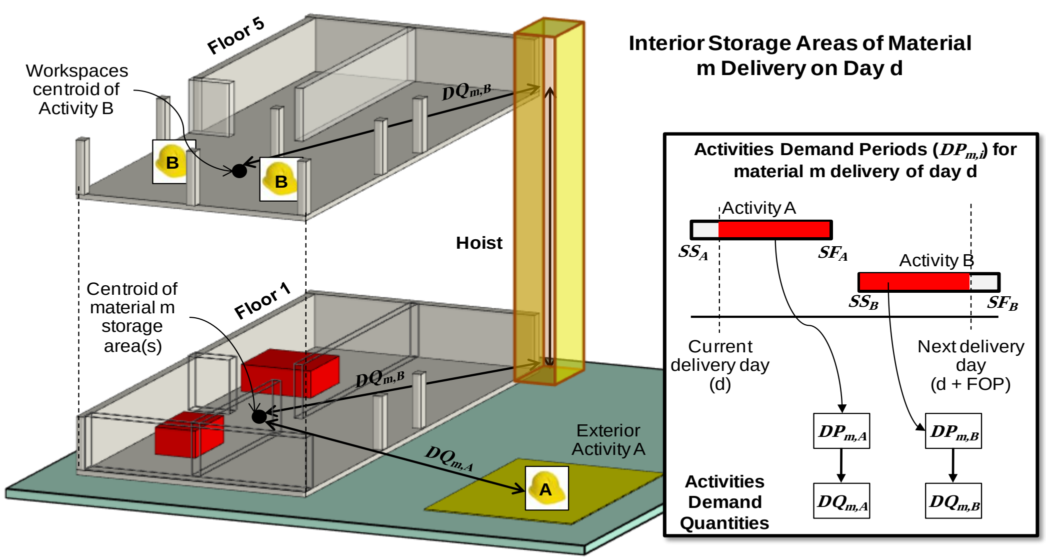


Figure 5.14 Interior Material Handling of Activities Demand Quantities

$$MHCI_{m,i}^{d} = \begin{cases} C_{m,i}^{d} \times D_{m,i}^{d} & \overline{D}_{m,i}^{d} = 0 \\ C_{m,i}^{d} \times D_{m,H}^{d} + \overline{C}_{m,i}^{d} \times \overline{D}_{m,i}^{d} + C_{m,i}^{d} \times D_{H,i}^{d} & otherwise \end{cases} \tag{5.16}$$

$$C_{m,i}^{d} = \frac{2 \times (DQ_{m,i}^{d} / q_{cr}) \times HCR_{cr}}{v_{cr}} \tag{5.17}$$

$$\overline{C}_{m,i}^{d} = \frac{2 \times (DQ_{m,i}^{d} / q_{H}) \times HCR_{H}}{v_{H}} \tag{5.18}$$

Where,

$MHCI_{m,i}^{d}$ = Interior handling cost of material *m* from day *d* delivery storage area(s) to activity *i* workspaces;

$C_{m,i}^{d}$, $\overline{C}_{m,i}^{d}$ = travel cost rate of handling crew and vertical hoist for transporting $DQ_{m,i}^{d}$ quantity of material *m* from its interior storage area(s) of day *d* delivery to activity *i* workspaces;

$D_{m,i}^{d}$, $\overline{D}_{m,i}^{d}$ = horizontal and vertical distance between activity *i* workspaces centroid and centroid of material *m* storage area(s) of day *d* delivery in room *r* and neighboring rooms (if needed);

$D_{m,H}^{d}$ = horizontal distance between material *m* interior storage area(s) of day *d* delivery and material vertical hoist;

$DQ_{m,i}^{d}$ = demand quantity of activity *i* material m between current and next delivery days;

q_{cr}, q_{H} = handling capacities of handling crew *cr* and material vertical hoist;

HCR_{cr} , HCR_H = hourly cost rate of handling crew *cr* and material vertical hoist ($/hour); and

v_{cr} , v_H = speed of handling crew *cr* and material vertical hoist (m/hour).

5.6 Application Example

An application example is analyzed to evaluate the performance of the present C2LP model and demonstrate its new capabilities in optimizing construction logistics planning of congested construction sites. The example represents the construction of a 10-storey building on a congested site that has exterior space of 120 square meters, as shown in Figure 5.15. This scarce exterior space is needed to position four temporary facilities over the construction duration: tower crane, site office trailer, waste disposal bin, and labors rest area, as shown in Table 5.1. In addition, four construction materials need to be stored onsite in this application example: concrete reinforcement steel (rebar), masonry blocks, drywall panels, and ceramic tiles. The construction schedule includes 107 activities, which are organized in four main groups as shown in Table 5.2: (1) substructure activities, (2) first floor activities, (3) typical floors activities, and (4) exterior activities. The construction duration is divided into three main stages that represent major changes in space demand and availability: (1) first stage starts with foundation works and finishes by the completion of the first floor skeleton work; (2) second stage starts with the second floor skeleton works and finishes by the completion of the sixth floor; and (3) third stage starts with sevens floor skeleton work and finishes by the tenth floor finishes. Figure 5.16 depicts the cumulative demand profiles of the four considered materials based on the activities early times.

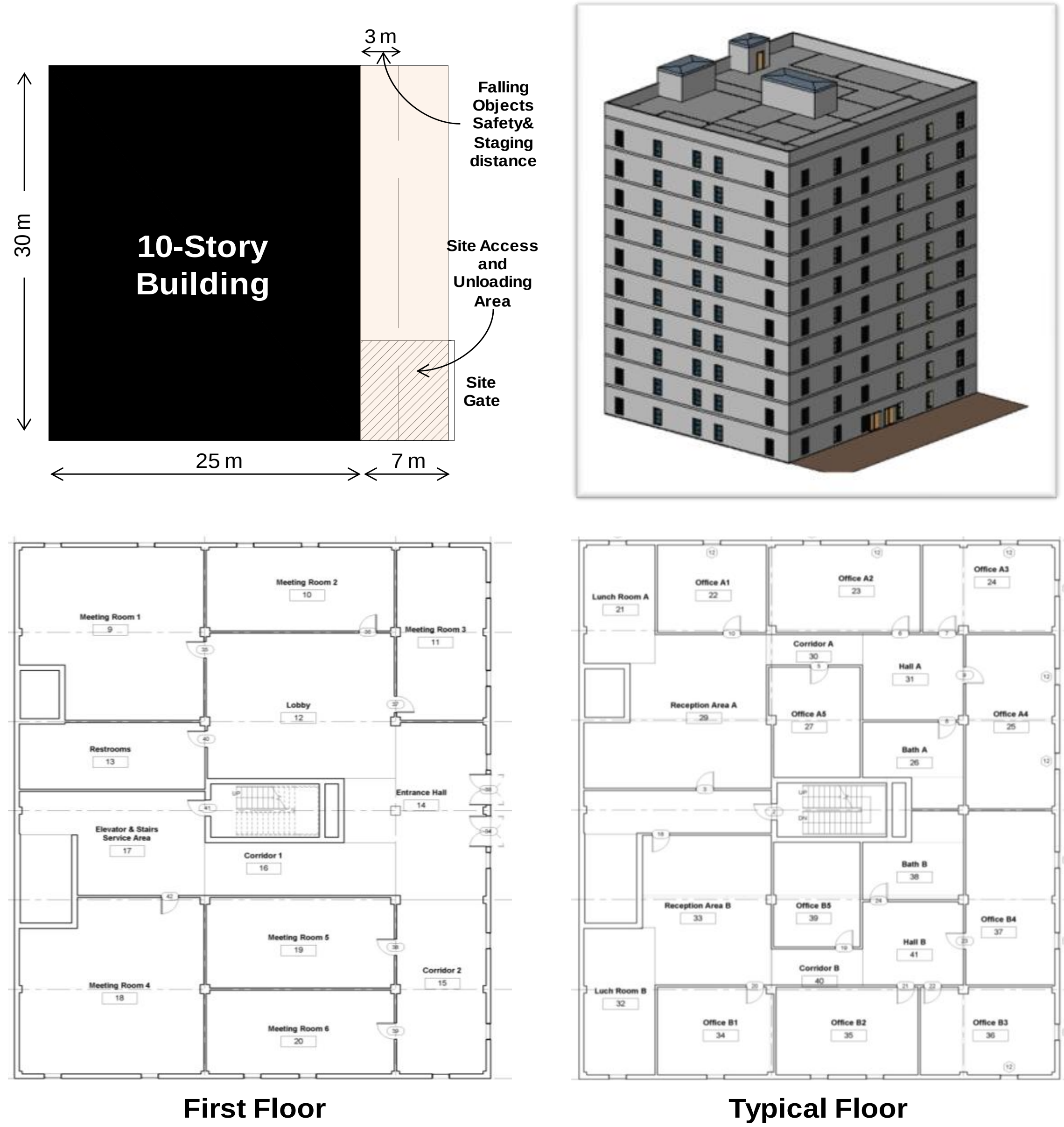


Figure 5.15 Site Exterior and Interior Spaces of the Application Example

Table 5.1 Geometry of Site Facilities

ID	Description	dimensions		Type*	Relocation Cost
		Lx	Ly		
F1	Site Gate	0.5	8	FX	N/A
F2	Tower Crane	3	3	ST	N/A
F3	Office trailer	10	3	MO	6000
F4	Waste Disposal Bin	7	2	MO	500
F5	Labor Rest Area	3	3	MO	500

** FX = Fixed   ST = Stationary   MO = Moveable*

Table 5.2 Construction Activities and Material Demand

Category	Activity Name	Duration	Material Demand
Sub-structure	Bored Foundation Piles	6	-
	Pile Caps	8	8 tons Rebar
First Floor	Columns Construction	5	13.3 tons Rebar
	Slab on grade	2	3.8 tons Rebar
	Roof Construction	12	17.8 tons Rebar
	Exterior Brickwork	4	4,000 Masonry Blocks
	Interior partitions Studs	4	-
	Electrical work	5	-
	Plumbing	2	-
	HVAC	3	-
	Interior Partitions Drywall	2	652.78 m^2 Drywall
	Tiling	6	700 m^2 Tiles
	Walls and Ceiling Finishes	3	-
Typical Floors	Columns Construction	5	13.3 tons Rebar
	Roof Construction	12	17.8 tons Rebar
	Exterior Brickwork	4	4,000 Masonry Blocks
	Interior partitions Studs	5	-
	Electrical work	7	-
	Plumbing	2	-
	HVAC	3	-
	Interior Partitions Drywall	3	1,023.5 m^2 Drywall
	Tiling	6	700 m^2 Tiles
	Walls and Ceiling Finishes	5	-
Exterior	Columns Construction of Staircase Room	3	9.7 tons Rebar
	Construction of Staircase Roof	8	1.8 tons Rebar
	Brickwork of Roof Parapet and Staircase	2	1,800 Masonry Blocks
	Exterior Finishes	7	-

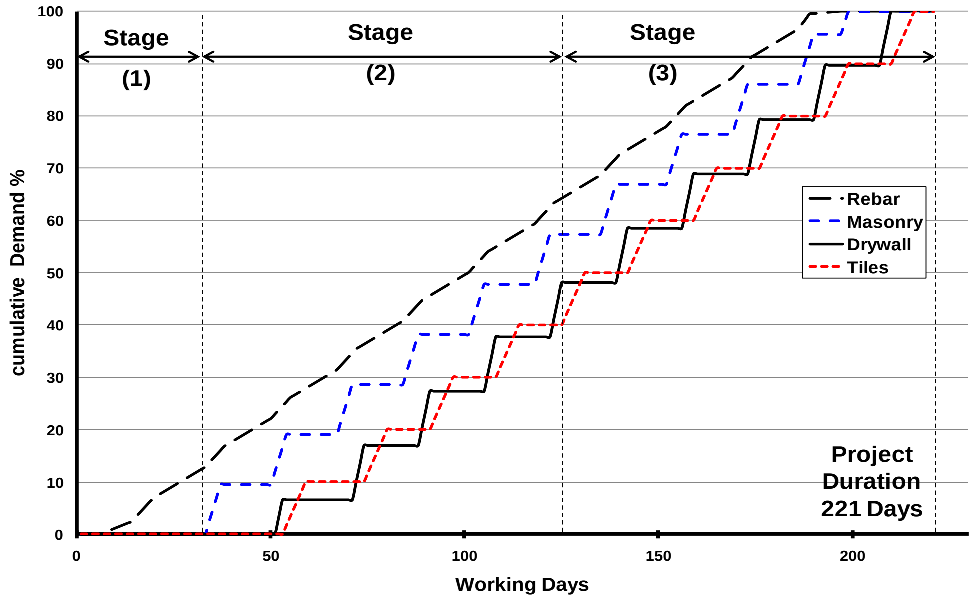


Figure 5.16 Material Cumulative Demand Profile based on Activities Early Times

In order to generate optimal logistics plans in this example congested project, the Input and Data Processing Module of the present C2LP model is invoked to identify the following data: (1) dimensions of site exterior space and its selected grid spacing of 1 meter, as shown in Figure 5.15; (2) interior space of the building under construction which consists of 193 rooms including 12 rooms in the first floor, 20 rooms in each of the nine repetitive floors, and one room that represent the space on the roof of the building, as shown in Figure 5.15; (3) construction schedule that includes construction stages, activities list, activities relationships, materials, and material assignment to activities as shown in Table 5.2 and Figure 5.16; (4) temporary facilities data, as shown in Table 5.1; (5) workspaces of interior activities by defining the required areas in each building room, such as the example shown in Figure 5.17 for workspaces of the first floor activities; (6) workspaces of exterior activities (foundation, first floor columns, and slab on grade activities) that are modeled to occupy the whole area of the building footprint; (7) partitioning activity of each floor, which is modeled to be studs erection of interior partitions in every floor; (8) permissible periods of interior storage areas of the considered materials, as shown in Table 5.3; (9) rooms creation time of each typical floor that is defined as the completion of previous floor's roof construction activity, and creation time of first floor rooms that is linked to the completion of slab-on-grade activity; (10) exterior space layout constraints as shown in Table 5.4; (11) material handling crews and equipments, as shown in Table 5.5; (12) suppliers data to identify their maximum possible ordering quantities and average delivery delay, as shown in Table 5.5; (13) material logistics data to define purchase cost, delivery cost, and footprint schedule each material, as shown in Table 5.6; and (14) planning parameters as shown in Table 5.7.

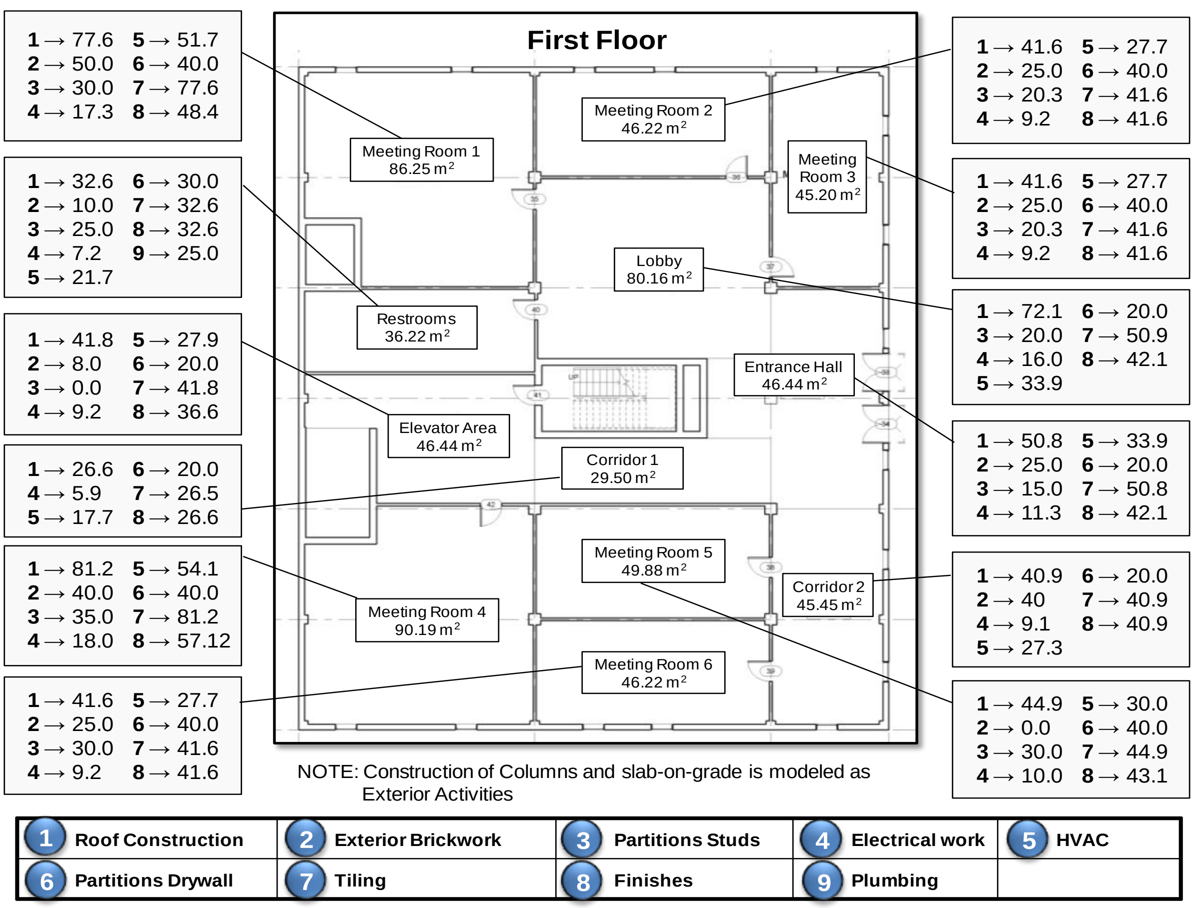


Figure 5.17 Example of Defined Activities Workspace in m² for the First Floor

Table 5.3 Materials Permissible Storage Periods in Interior Spaces

Material	Permissible Storage Period*
Rebar and Masonry	Roof → Plumping Activity of each floor
Drywall Panels	Roof → Drywall Activity of each floor
Tiles	Plumping → Finishes Activity of each floor

* measured from scheduled finish times of listed activities

Table 5.4 Exterior Site Layout Constraints

Distance Constraints			
Purpose	**Type**	**Facilities[1]**	**Distance (m)**
Safety	Min	B, F3	3
	Min	B, F5	3
Operational	Max	F1, F4	4
	Max	B, F2	2
	Min	B, M	3

Exclusion Zone Constraints (Operational)[2]				
Facility	**X1**	**X2**	**Y1**	**Y2**
All site facilities	25	32	0	8

[1]: B = building, F1 = first facility, M = all material storage areas
[2]: All coordinates are measured from the left bottom corner of the site

Table 5.5 Material Onsite Handling and Suppliers Data

Material	Onsite Handling					Suppliers	
	Handling Crew/ Equipment	Type *	Handling Quantity q_{mi}^{r}	Travel Speed v_r (m/hr)	Hourly Cost HCR_r ($/hr)	Max Order Quantity	Average Delivery Delay
Rebar	Forklift Crew Tower Crane	H V	2 tons	5,000 5,000	200 200	100 tons	0.1
Masonry Blocks	Forklift Crew Hoist	H V	500 unit	10,000 2,700	125 150	20,000 units	0.3
Drywall Panels	Forklift Crew Hoist	H V	100 m^2	10,000 2,700	125 150	700 m^2	0.5
Tiles	Forklift Crew Hoist	H V	75 m^2	10,000 2,700	125 150	2,000 m^2	0.9

* Handling Type: H = horizontal handling, V = vertical handling

Table 5.6 Purchase Costs, Delivery Costs, and Storage Footprints of Construction Materials

ID	Material	unit	**Purchase Cost** ($/unit)			**Delivery Cost** ($)		**Storage Footprint**		
			Stage t	**Quantity** Q	**rate** $PCR^t(Q)$	**Quantity** Q	**Cost** $DLC^t(Q)$	**Quantity** Q	**Lx** (m)	**Ly** (m)
M1	Rebar	ton	1	0 → 100	650	0 → 25	600	0 → 32	15	2
			1	100 → 200	550	25 → 50	1200	32 → 64	15	4
			2,3	0 → 100	750	50 → 75	1800	64 → 96	15	6
			2,3	100 → 200	650	75 → 100	2400	96 → 128	15	8
M2	Masonry Blocks	1000 units (M)	1 → 3	0 → 10	1,100	0 → 3	600	0 → 1	2.5	2.5
			1 → 3	10 → 30	950	3 → 6	1200	1 → 2	5	2.5
						6 → 9	1800	2 → 4	5	5
						9 → 12	2400	4 → 6	7.5	5
						12 → 15	3000	6 → 9	7.5	7.5
						15 → 18	3600	9 → 12	10	7.5
						18 → 21	4200	12 → 16	10	10
								16 → 20	12.5	10
M3	Drywall Panels	m^2	1 → 3	0 → 720	3	0 → 360	600	0 → 360	1.5	3
			1 → 3	720 → 2160	2.8	360 → 720	1200	360 → 720	3	3
			1 → 3	2160 → 3000	2.5	720 → 1080	1800	720 → 1080	4.5	3
						1080 → 1440	2400	1080 → 1040	4.5	4.5
						1440 → 1800	3000	1040 → 1800	4.5	6
						1800 → 2160	3600	1800 → 2160	6	6
						2160 → 2520	4200	2160 → 2520	7.5	6
						2520 → 2880	4800	2520 → 2880	7.5	7.5
M4	Tiles	m^2	1 → 3	0 → 2000	50	0 → 500	600	0 → 250	2.5	2.5
			1 → 3	2000 → 4000	45	500 → 2000	1200	250 → 500	5	2.5
						2000 → 2500	1800	……	……	……
						2500 → 4000	2400	2500 → 2750	15	15

Table 5.7 Planning Parameters

Planning Parameter	Value(s)
Daily Project Interest	0.03%
Project liquidated damage (LQD)	$25,000/day
Time-depended indirect cost (TDIC)	$5,000/day
Possible fixed-ordering-periods for all materials (FOP)	1, 14, 21, 28 days
Site Grid Spacing	1 meter
Interior Space Utilization Factor (SUF)	0.9

The present C2LP module was utilized to process and analyze the aforementioned input data and to generate optimal logistics plans that represent unique and non-dominated tradeoffs between the conflicting objectives of minimizing total logistics cost and minimizing project schedule criticality. First, the defined input data are manipulated in order to construct the space demand profile for each room and workspaces centroid for each interior construction activity. Second, the GA chromosome (see Figure 5.5) is formulated to represent 152 decisions variables, which are classified in four main categories: (1) twelve procurement decisions that identify fixed-ordering-periods (FOP) of every material in each stage; (2) forty eight material storage decision variables that identify material storage type, exterior grid locations, exterior layout orientation, and interior storage priority of each material in every stage; (3) sixteen decision for temporary facilities site layout that include one location decision for positioning the tower crane (stationary facility) in the first stage, 9 location decisions for the other three moveable temporary facilities (office trailer, waste bin, and labor rest area) in each stage, and 6 orientation decisions for non-square facilities (office trailer and waste bin) in every stage; and (4) seventy six decisions of minimum-shifting-days of each noncritical activity. Third, 462 constraints are identified for the present example that include layout constraints (overlap, boundary, distance, and zone constraints) as well as interior space capacities, rooms creation times, and material permissible storage periods. Fourth, the present C2LP is utilized to search for optimal tradeoff solutions for this highly-constrained and complex problem, which includes 1.6×10^{240} possible solutions based on the different combinations of optimization decision variables.

The present model generated 361 optimal solutions that represent a wide spectrum of tradeoffs between minimizing construction logistics cost and minimizing schedule criticality. As shown in Figure 5.18, these solutions range from: (1) the minimum logistics cost solution of $1,096,466 that is represented by solution A and resulted in the highest criticality index (0.544) of all generated solutions; and (2) zero schedule criticality index solution that is represented by solution B that causes the maximum construction logistics costs of $1,458,381. This varied set of optimal solutions enables construction planners to choose construction logistics plans that best fits the specific needs of the project analyzed. To illustrate the capabilities of the developed framework, the two extreme solutions are analyzed in more details.

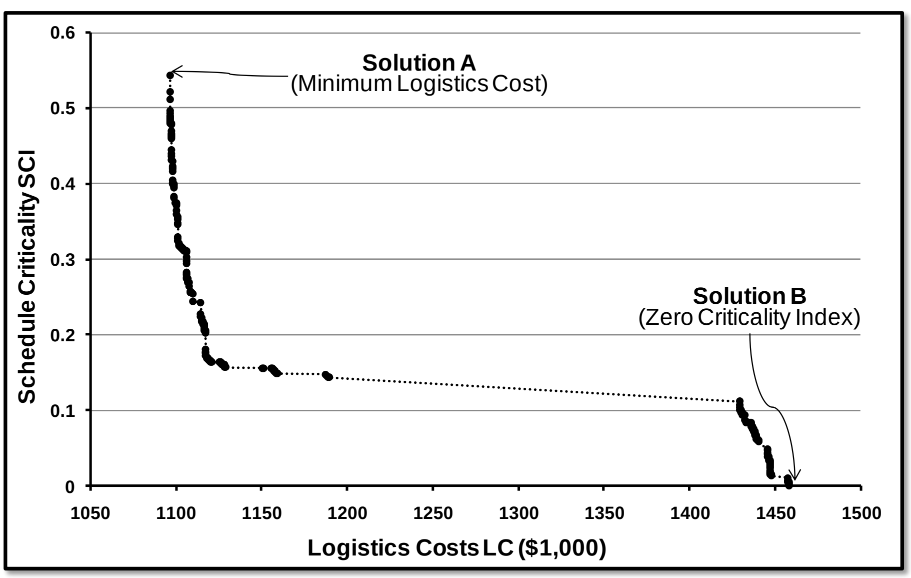


Figure 5.18 Generated Pareto Optimal Solutions

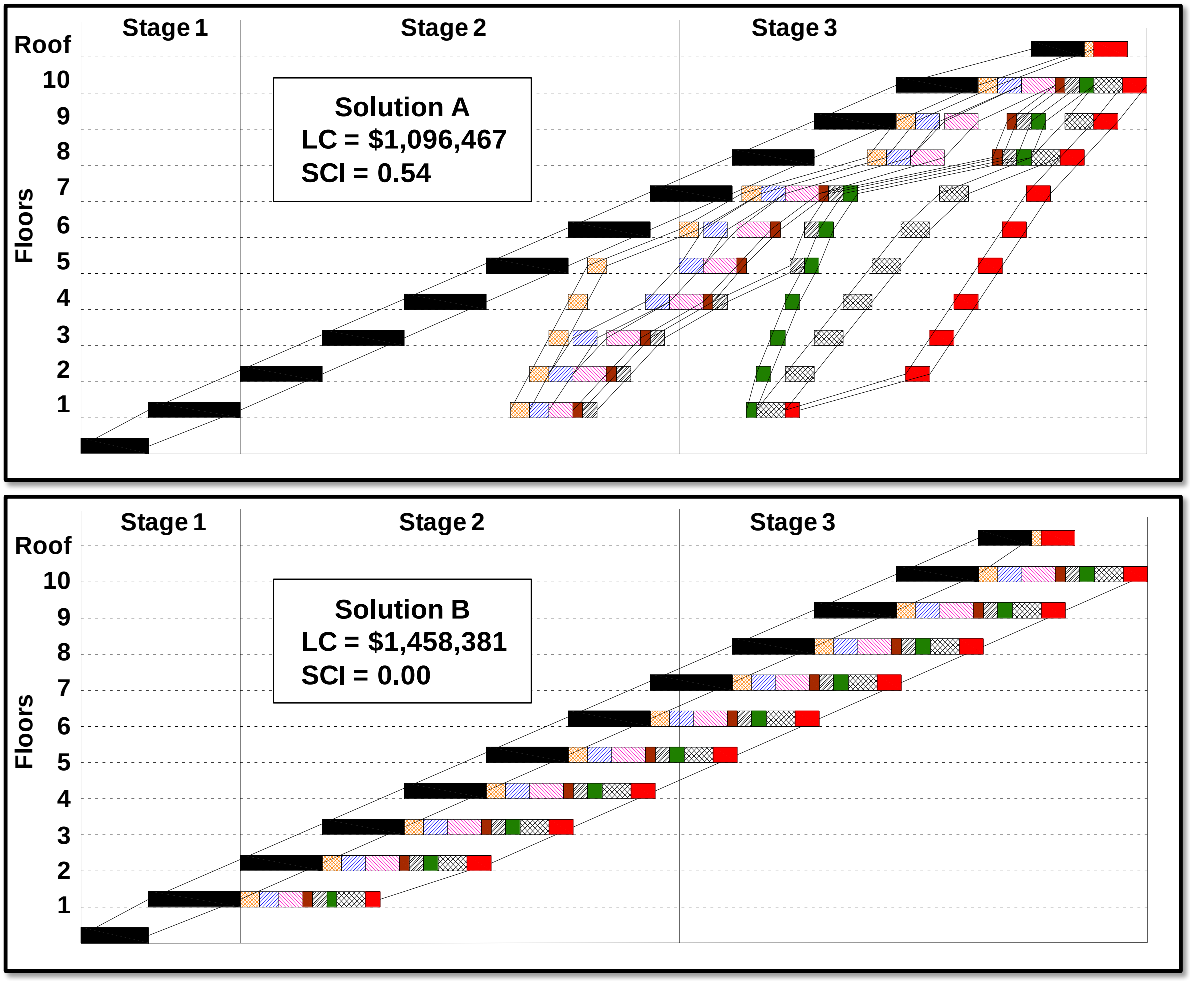
Logistics costs are minimized in solution A by procuring construction material in fewer deliveries that are stored in building interior spaces with minimal shifting of noncritical activities. As shown in Figure 5.19, the activities early times do not permit sufficient space for interior material storage because of the early scheduling of: (1) partitioning activities (partition studs) that leads to the breakdown of material storage areas over floor rooms with fewer storage capacities and the inability to accommodate large storage dimensions, such as rebar; (2) ending activities of permissible storage periods that results in insufficient periods of time for the storage of rough materials such as masonry. Accordingly, the present model generated minimal shifts of noncritical activities in solution A, as shown in Figure 5.19, which are necessary to create sufficient interior storage spaces in order to facilitate material procurement in large fixed-ordering-periods with low ordering and stock-out costs, as shown in Table 5.8. For example, rebar is procured in 21 days ordering periods and stored in building interior space during the second stage because of the generated shifts of the partition activities that allow the accommodation of large storage areas for rebar before floor space is partitioned, as shown in Figure 5.20. Nevertheless, a Just-in-Time procurement (FOP = 1 day) is selected for rebar in first and third stages, as shown in Table 5.8, because the first floor interior space is occupied by its slab construction activity during the first stage while the partitioning activities total float during the third stage do not permit enough shifting to create the required interior storage periods for rebar. On the other hand, the masonry blocks and drywall panels are stored in building rooms during the third stage by extending their permissible storage periods using minimal shifting of plumping and drywall activities, as shown in Figure 5.20.

Table 5.8 Material Procurement Decisions and Construction Logistics Costs

Solution A					
Procurement Decisions and Costs		Rebar	Masonry	Drywall	Tiles
Stage 1	FOP	1 day (JIT)	N/A*	N/A*	N/A*
	Ordering Cost	$44,039.5			
	Financing Cost	0			
Stage 2	FOP	21 days	28 days	N/A*	N/A*
	Ordering Cost	$133,022	$23,200		
	Financing Cost	$357.77	$62.28		
Stage 3	FOP	1 day (JIT)	14 days	14 days	14 days
	Ordering Cost	$134,608	$29,380	$34,603	$356,600
	Financing Cost	0	$34.35	$40.29	$597.74
Stock-out Cost		$330,000 (expected delay = 11 days)			
Travel Cost		$9922.2			
Relocation Cost		$0			
Material Handling Cost		$521.4			

Solution B					
Procurement Decisions and Costs		Rebar	Masonry	Drywall	Tiles
Stage 1	FOP	1 day (JIT)	N/A*	N/A*	N/A*
	Ordering Cost	$44,039.5			
	Financing Cost	0			
Stage 2	FOP	1 day (JIT)	1 day (JIT)	1 day (JIT)	1 day (JIT)
	Ordering Cost	$182,223	$40,800	$21,017.3	$154,400
	Financing Cost	0	0	0	0
Stage 3	FOP	1 day (JIT)	1 day (JIT)	1 day (JIT)	28 days
	Ordering Cost	$134,608	$30,380	$25,976.6	$214,800
	Financing Cost	0	0	0	$698
Stock-out Cost		$600,000 (expected delay = 20 days)			
Travel Cost		$9922.2			
Relocation Cost		$0			
Material Handling Cost		$38.86			

* there is no material demand during this stage



ID	Name	ID	Name
1	Concrete	6	HVAC
2	Masonry	7	Drywall
3	Partition Studs	8	Tiling
4	Electrical	9	Finishes
5	Plumping		

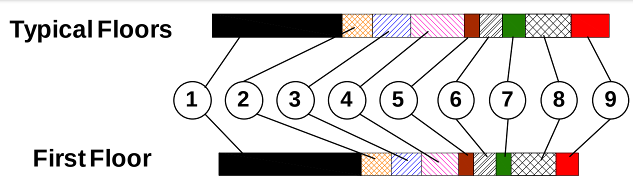


Figure 5.19 Activities Scheduled Times of Generated Solutions A and B

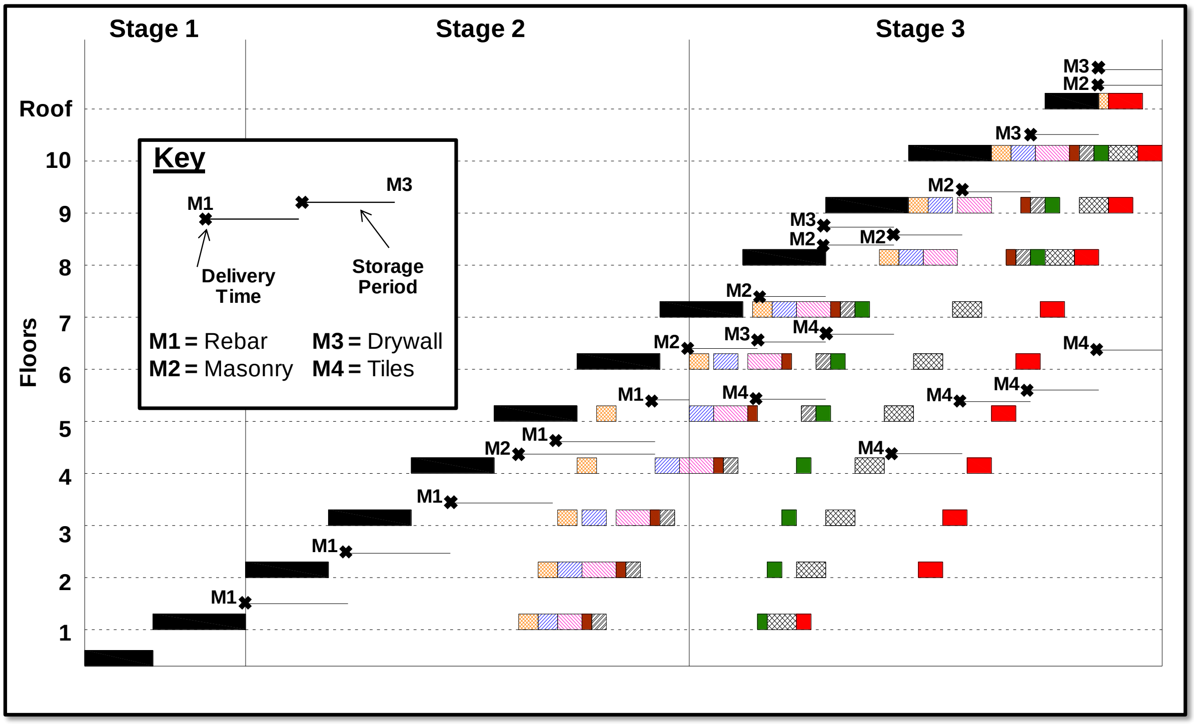


Figure 5.20 Material Delivery Times and Interior Storage Periods in Solution A

On the other hand, solution B minimizes the project criticality index and accordingly generates optimal material procurement plans that maintain the early times of interior construction activities. In this solution, all noncritical activities are scheduled on their early times which result in a zero schedule criticality index (SCI). Accordingly, Just-in-Time procurement plans are generated for all construction materials, as shown in Table 5.8, except for tiles in the third stage that are procured in fixed ordering periods of 28 days because of the completion of rough activities (from concrete to plumping activities) of the building's lower floors. This solution resulted in the maximum logistics costs as a result of material frequent deliveries (JIT procurement), which lead to: (1) high purchase costs because of the loss of suppliers discounts on large ordering quantities; (2) high delivery costs because of the inefficient utilization of truck capacities; and (3) high stock-out cost due to the higher risk of material unavailability and project delay as a result of late suppliers deliveries.

The present C2LP model generated optimal exterior site layout plans that minimize layout costs while complying with all imposed geometric constraints, as shown in Figure 5.21. The Dynamic site layout plan is optimized in all generated solutions by minimizing resources travel costs and eliminating unnecessary facilities relocation costs. The generated locations and orientations of site temporary facilities comply with all imposed layout geometric constraints (see Figure 5.21) as follows: (1) all temporary facilities are positioned outside of the site access area that is modeled using an exclusion zone; (2) the construction waste disposal bin is located within 4 meters of the site gate to facilitate its truck hauling; (3) the office trailer and labor rest area are positioned out of the failing-objects risk distance around the building that is represented by a minimum distance constraint between these facilities and the building; and (4) the tower crane is located within the two-meters maximum distance constraint from the building, which is required for its bracing to the constructed structure.

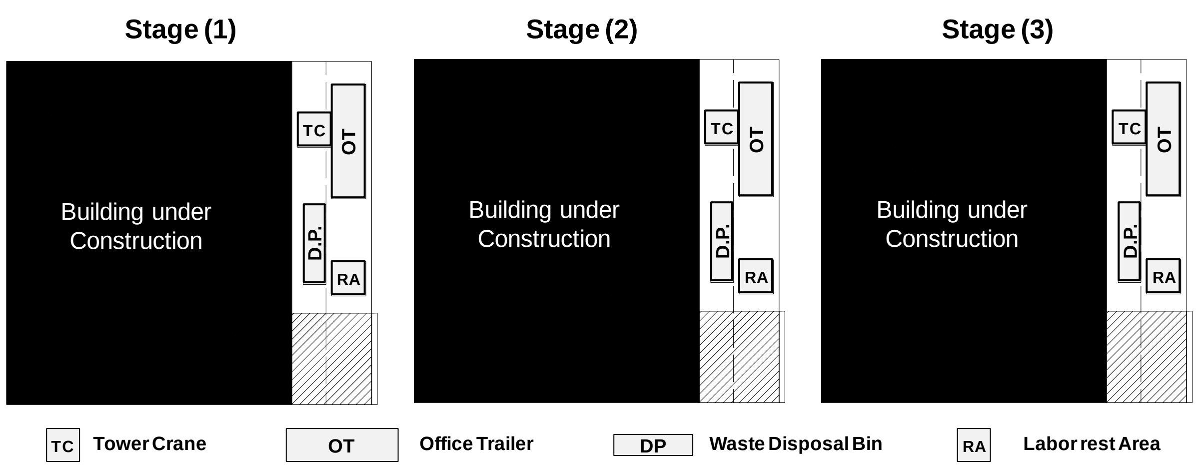


Figure 5.21 Optimal Exterior Layout Plans for all Generated Solutions

5.7 Summary

This chapter described the development of a new multi-objective optimization model for congested construction logistics planning (C2LP) that is designed to help planners in utilizing interior building spaces and generating optimal logistics plans that minimize total logistics cost while minimizing the adverse impacts of interior material storage on project schedule. Interior building space is represented as a set of non-identical rooms that can be defined based on project architectural drawings, while exterior space is modeled as a grid of locations with planner-specified fixed spacing. As such, the present model utilizes multi-objective Genetic Algorithms to formulate and optimize four main categories of decision variables: (1) material procurement; (2) materials storage plan; (3) temporary facilities site layout; and (4) scheduling of noncritical activities. The C2LP model utilizes Genetic Algorithms to generate optimal tradeoff solutions of these decision variables, which provide a wide spectrum of tradeoffs between the two conflicting objectives of minimizing total logistics costs and project schedule criticality. Interior material storage plans are generated using novel computational algorithms that consider four main types of interior storage constraints: room space capacities, room creation times, rooms partitioning times, and permissible material interior storage periods. Furthermore, other new algorithms are developed to calculate material interior and exterior handling costs as well as shifting of noncritical activities. The performance of the present model was evaluated using an application example that illustrates its capabilities in optimizing logistics planning on congested construction sites.

CHAPTER 6
AUTOMATED MULTI-OBJECTIVE CONSTRUCTION LOGISTICS OPTIMIZATION SYSTEM

6.1 Introduction

This chapter presents the development of an Automated Multi-objective Construction Logistics Optimization System named “AMCLOS”. The main objective of the system is to support construction planners in optimally planning material procurement and storage with unique modeling capabilities for congested construction sites. To this end, AMCLOS is designed and implemented to provide a number of new and unique capabilities, including: (1) automated detection and retrieval of exterior and interior spatial data of the construction site from already available design electronic documents, such as Building Information Models (BIM); (2) fast and easy input of construction schedule data by reading available schedule data from commercially available project planning software packages; (3) seamless integration of project spatial data that facilitates the definition of various types of spatio-temporal linking and storing all input data in a relational database; (4) utilizing multi-objective optimization and computational algorithms in order to simultaneously minimize total logistics planning and project schedule criticality; and (5) interactive data input and reporting of generated optimization results.

In order to provide the aforementioned capabilities, AMCLOS is implemented in Microsoft Visual Studio C++ programming Environment in four main modules, as shown in Figure 6.1: (1) site spatial data retrieval module to facilitate automated identification of site exterior dimensions and building geometric attributes, which exist in the IFC (International

Foundation Classes) file of the project's Building Information Model; (2) schedule data retrieval module to import construction activities, materials, activities relationships, and activities-materials assignments from a commercially available project planning software, Microsoft Project; (3) relational database module to provide seamless integration of site space schedule, and logistics data and detect any inconsistencies in spatio-temporal linkages defined by the planner, and store all defined data in a shared database; and (4) graphical user interface module to facilitate the input of project spatial, schedule, and logistics data and the reporting of generated optimal logistics plans. These five main modules are described in more detail in the following sections.

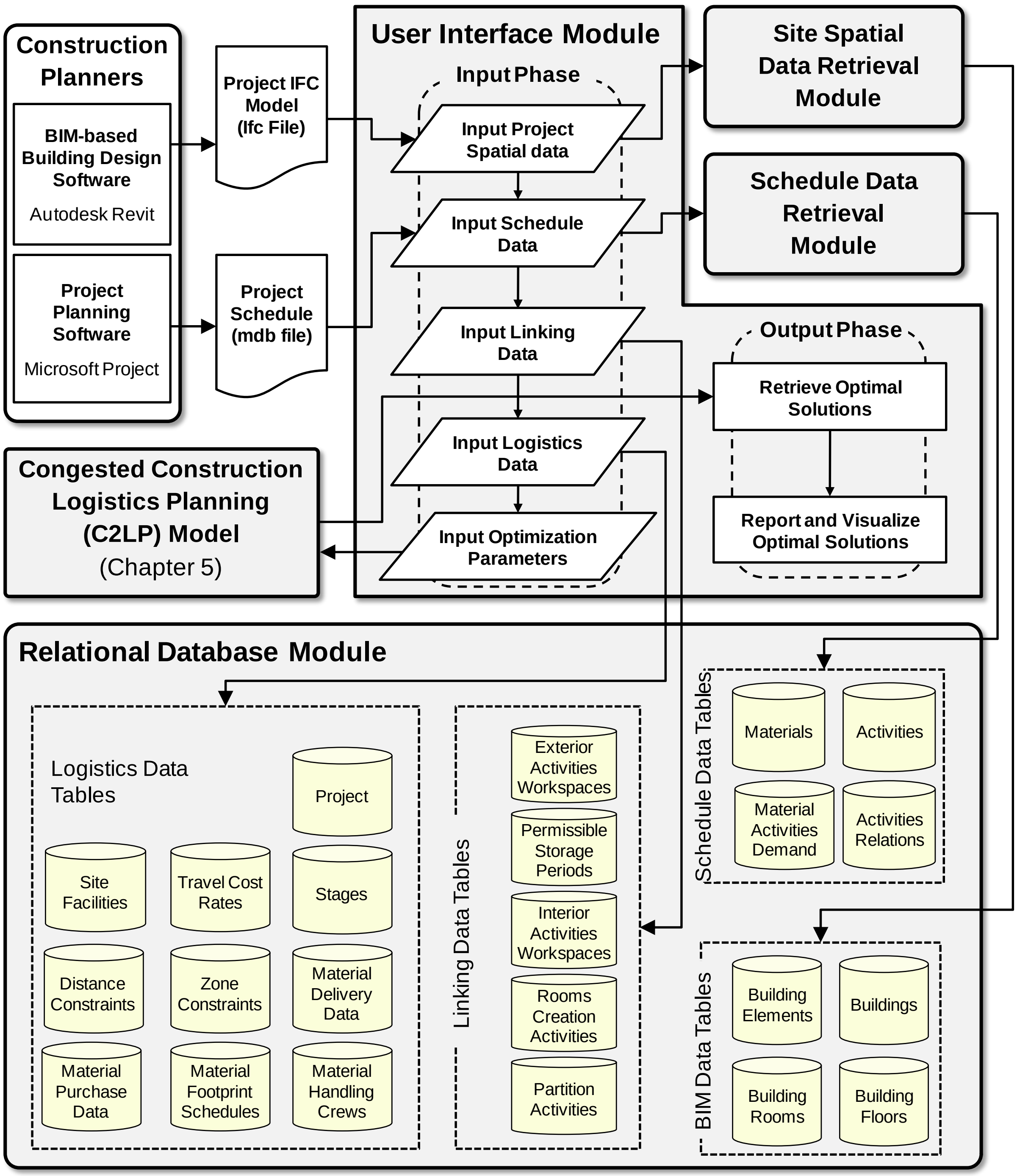


Figure 6.1 AMCLOS Main Implementation Modules

6.2 Site Spatial Data Retrieval Module

The purpose of this module is to facilitate automated detection and retrieval of construction site spatial data from existing Building Information Models (BIM) of the project. Building Information Modeling is an object-oriented approach that enables storing multi-disciplinary information within one virtual representation in order to enhance collaboration between project parties and reduce redundancy of planning and engineering efforts (Schlueter and Thesseling 2009). This module is designed to retrieve from the project's BIM files the geometric attributes of the construction site, buildings under construction, and buildings rooms. First, the project's building information model is exported from commercially available design software packages (such as Autodesk Revit) in an IFC 2x3 (Industry Foundation Classes) file format, which is a non-proprietary and interoperable data model of buildings that was developed by the International Alliance for Interoperability (IAI 2010). Second, an open source dynamic-link library, named IFCEngine.dll (TNO 2009) is integrated in the system to enable parsing the exported IFC file and identifying the geometric attributes of the construction site and buildings under construction, as explained in following subsections.

6.2.1 Identification of Site Boundaries

The construction site boundary is represented by a 2D rectangle that is identified by the coordinates of its four corners. In IFC 2x3 Schema, the construction site is represented using *IfcSite* entity that may support different geometric representations such as survey points, meshes, solid bodies, and lines. As such, the site boundary coordinates are identified by locating the *IfcSite* entity and performing the following three main steps, as shown in Figure

6.2: (1) retrieving *IfcProductRepresentation* entity using the connecting attribute (i.e. *Representation*)), which contains all *IfcSite* geometric representations *IfcRepresentation*; (2) looping over these representations of the *IfcProductRepresentation* using its "*Representations*" attribute and selecting the 2D curve representation that has "*RepresentationType*" attribute equals Curve2D; and (3) identifying the coordinates of the construction site boundary corners ($SiteX_{min}$, $SiteY_{min}$, $SiteX_{max}$, and $SiteY_{max}$) by obtaining the "*Coordinates*" attribute of each *IfcCartesianPoint* entity of Curve2D *IfcRepresentation*, which is retrieved in the previous step. These coordinates are stored in AMCLOS database to be considered in the generation of site locations grid and the formulation of site boundary constraints that are imposed on all temporary facilities and material storage areas.

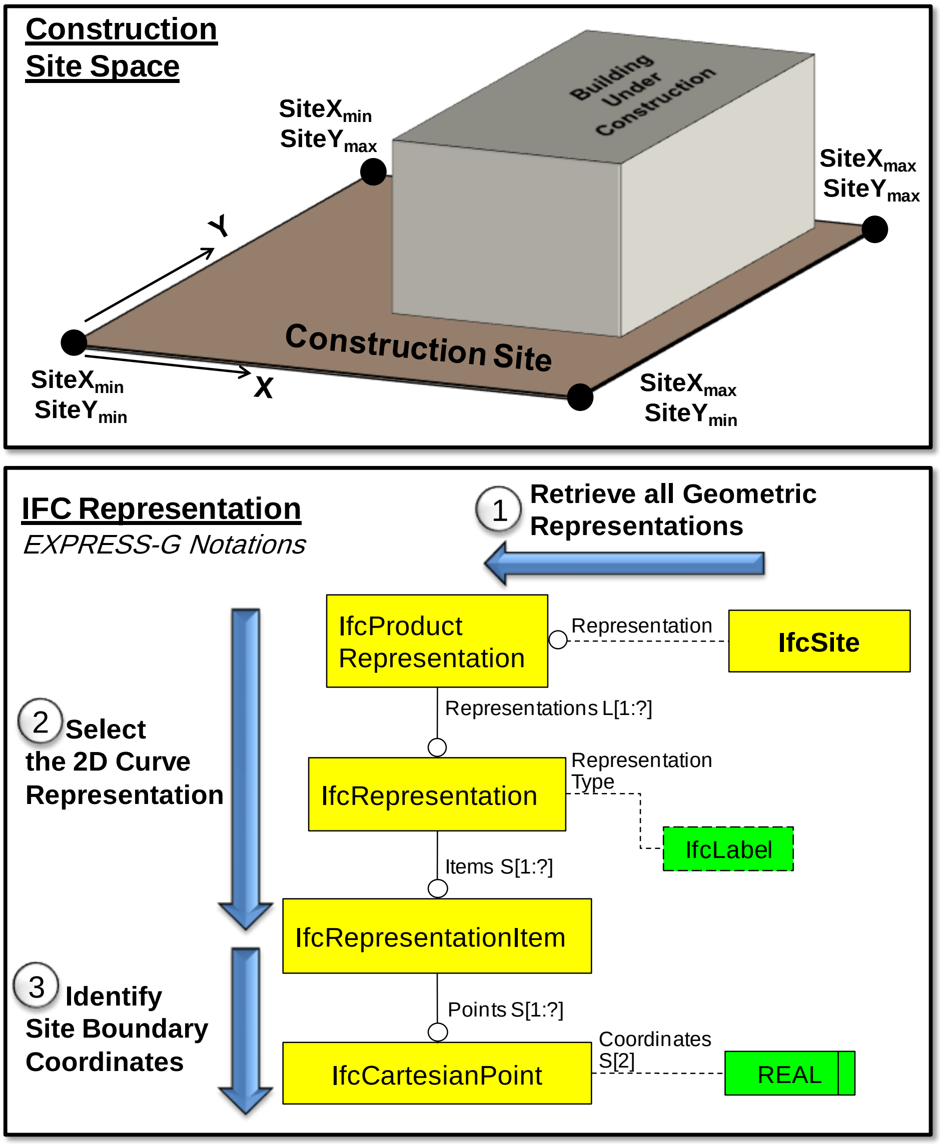


Figure 6.2 Automated Identification of Construction Site Space

6.2.2 Identification of Building Space

Optimal planning of construction logistics in the present AMCLOS system requires the identification of three main spatial attributes of each building under construction: building floors, coordinates of building footprint, and building rooms. First, building floors are represented using *IfcBuildingStorey* entity that has a decomposition relationship with its building entity *IfcBuilding*. Building floors are retrieved from the IFC-based model in two main steps: (1) getting the decomposition entity (*IfcRelDecomposes*) using the "*IsDecomposedBy*" attribute of *IfcBuilding* entity; and (2) recalling all building floors (*IfcBuildingStorey* entities) that are linked to the decomposition relationship entity IfcRelDecomposes through its attribute "*RelatedObjects*". Three attributes are stored in the AMCLOS database for each floor: "*Elevation*" (in meters), "*GlobalID*" (global unique identification string to be differentiated from other entities in the IFC model) and "*Name*" (e.g., first floor) that are inherited from its parent entities "*IfcProduct*" and *IfcSpatialStructureElement*. Building floors identification is needed to efficiently define spatio-temporal links between each floor construction activities and rooms such as floor partitioning and creation times.

Second, coordinates of building footprint are calculated as the bounding 2D box of all of its building elements as these coordinates are not explicitly modeled in the *IfcBuilding* entity. Accordingly, building footprint coordinates are calculated in three main steps: (1) recalling all building components that are represented in the IFC model using subtypes if *IfcBuildingElement* entity such as *IfcSlab*, *IfcColumn*, and *IfcWall*; (2) obtaining the vertices of each of these building components by using IFCEngine and specialized data structures of Microsoft DirectX 9.0; and (3) calculating the coordinates of building footprint (BX_{min}, BY_{min}, BX_{max}, and BY_{max}) as the bounding box of all building components using the obtained vertices of each element. Building footprint coordinates are used in the formulation of exterior space overlap constraints between buildings under construction and other site facilities, such as temporary facilities and material storage areas.

Third, the centroid and area of each building room are calculated in order to be utilized in positioning interior material storage areas. Building rooms are represented in the IFC model using *IfcSpace* entity (subtype of *IfcSpatialStructureElement* entity), which is used to provide geometric and functional information of interior building spaces that are bounded by building components. First, the centroids of building rooms are calculated using their vertices data using Microsoft DirectX 9.0 data structures, similar to the earlier described building components (i.e., *IfcSlab*, *IfcColumn*, etc.). These centroids are utilized in the calculation of interior handling distances between activities workspaces and material storage areas. Second, the area of each building room is obtained by tracking the IFC schema relationships between each *IfcSpace* entity and its corresponding *IfcQuantityArea* entity, which contains data on the room area. The area of each building room is obtained in three main steps: (1) *IfcRelDefinesByProperties* entity is identified for *each IfcSpace* entity using its "*IsDefinedBy*" attribute; (2) "*RelatingPropertyDefinition"* attribute of *IfcRelDefinesByProperties* entity is used to retrieve *IfcElementQuantity* entity that contains a set of physical quantities, such as length, volume, mass, and area; and (3) obtain the set of all physical quantities using "*Quantities*" attribute of *IfcElementQuantity* entity and search for *IfcQuantityArea* entity, which defines the room's area through its "*AreaValue*" attribute. The area of each building room is stored in AMCLOS database in order to be considered during the allocation of interior spaces to material storage areas.

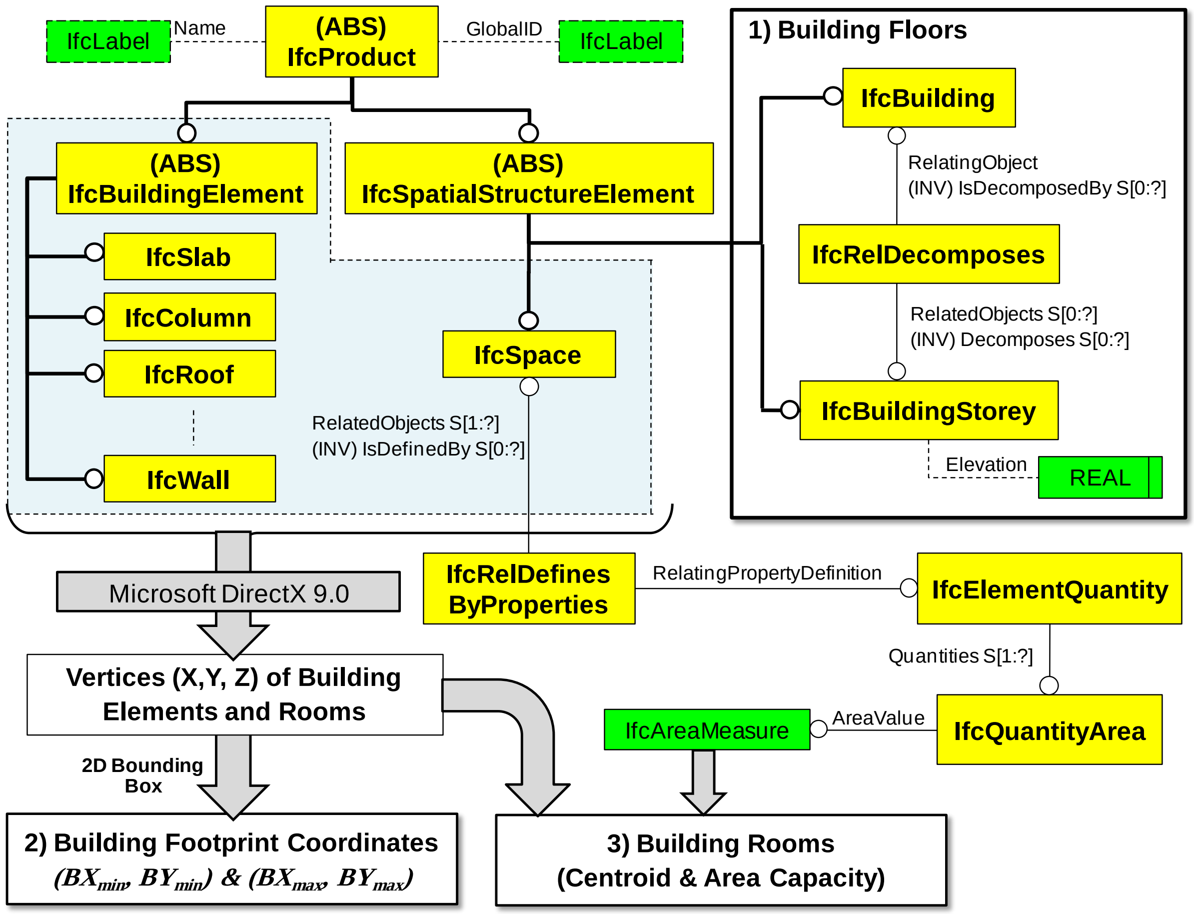


Figure 6.3 Automated Identification of Building Coordinates, Floors, and Rooms

6.3 Schedule Data Retrieval Module

The objective of this module is to obtain the project schedule data from readily available plans generated in Microsoft Project software. AMCLOS is designed to enable automated retrieval of this Microsoft Project schedule data, which is exported in a Microsoft Access database (mdb) file format. As such, the schedule data in the exported database file are retrieved using Microsoft Access Open Database Connectivity (ODBC) driver that enables the implementation of SQL query statements in Microsoft Visual Studio implementation environment. Four main categories of schedule data are obtained from the exported database file: activities, activities relationships, materials, and activities material demand. First, activities data are retrieved from a data table named “MSP_Tasks”, which stores activities indices, names, durations, early times (start and finish), total float, and free float. SQL statements are designed to select only the activities that satisfy the following conditions: (1) has a non-negative index; and (2) is not a milestone or summary activity. Second, activities relationships are obtained from the “MSP_Links” data table with the following data: index of predecessor activity, index of successor activity, relationship type, and relationship lag. Third, materials data are obtained from the “MSP_Resources” data table, which stores all project labor, equipment, and material resources, using a conditional SQL statement in order to obtain the indices and names of only material-type resources. Finally, the material demand of each activity is obtained from the “MSP_Assignments” data table by retrieving material indices, activities indices, and demand quantities.

6.4 Relational Database Module

The main purpose of this module is to develop a relational database that stores and integrates all input data required for construction logistics planning and optimization. This relational database module is designed to facilitate: (1) seamless storage and update of project input data considering their frequent change and modification by the users of the system; and (2) modeling all relationships and dependencies between input data in order to eliminate inconsistent and incomplete datasets. As such, this module is composed of 26 data tables that are organized in four main categories: building information model, schedule, linking, and logistics data. Figure 6.4 illustrates an entity relationship diagram that describes primary keys and main attributes of these tables and the relationships among them using a crow’s foot model (Rob and Coronel 2002). Tables 6.1 and 6.2 list all attributes of these tables and their brief description.

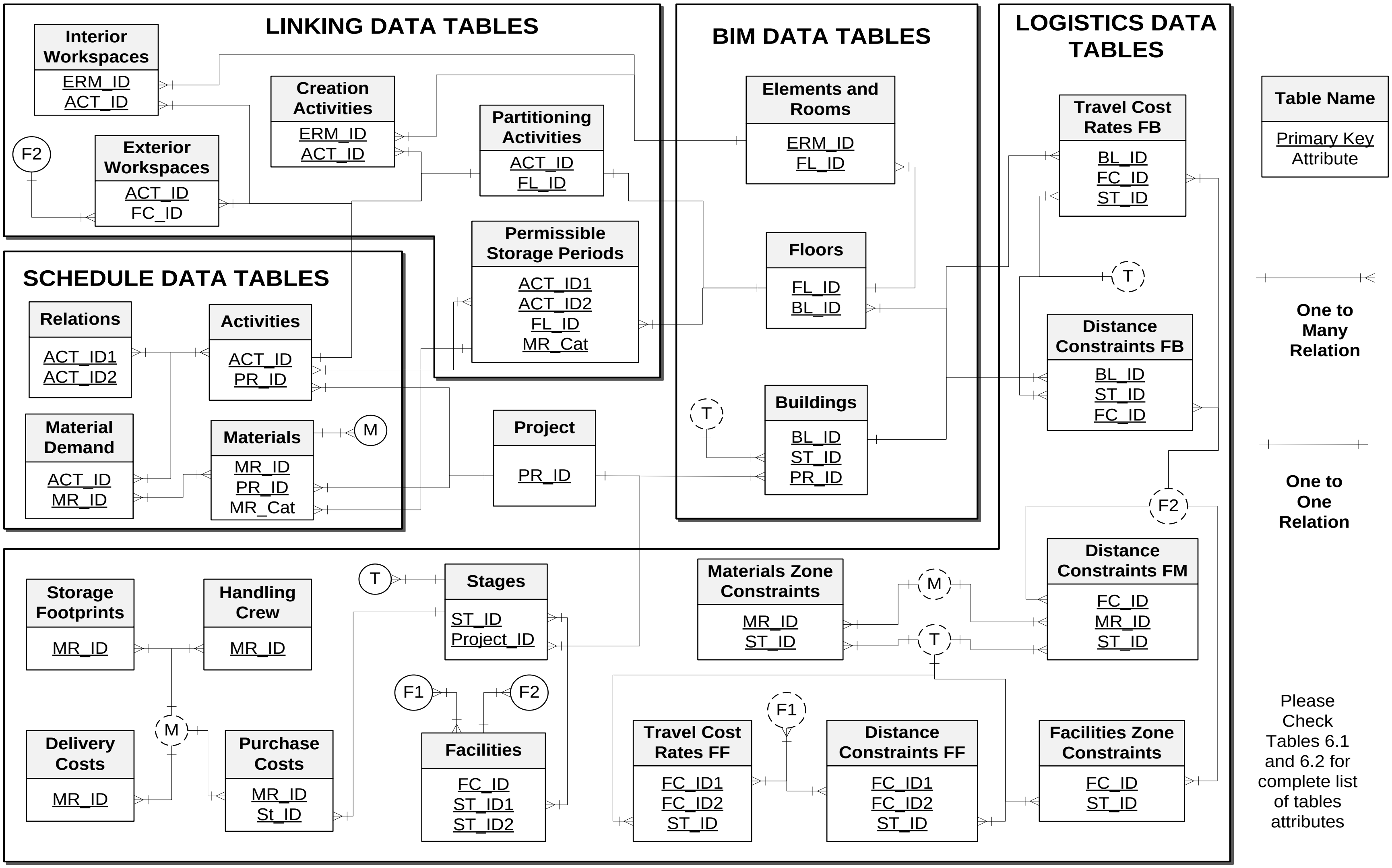


Figure 6.4 Entity Relationship Diagram of Relational Database Module

Table 6.1 Attributes of Project, BIM, Schedule, and Linking Data Tables

Projects
PR_ID = Project ID
PR_Xmin = Site min X Coordinate
PR_Ymin = Site min Y Coordinate
PR_Xmax = Site max X Coordinate
PR_Ymax = Site max Y Coordinate
PR_GrideS = Spacing of site locations grid
PR_DIR = Daily interest rate
PR_LQD = project liquidated damage
PR_DIC = Project daily indirect cost
PR_Elev = Project site elevation

Activities
ACT_ID = Activity ID
PR_ID = Project ID
ACT_Name = Activity Name
ACT_Dur = Activity Duration
ACT_ES = Activity early start
ACT_EF = Activity early finish
ACT_TF = Activity total float
ACT_FF = Activity free float

Activities Relations
RL_ID = Relation ID
ACT_ID1 = Predecessor Activity ID
ACT_ID2 = Successor Activity ID
REL_TY = Relation type
REL_Lag = Relation lag duration

Material Demand
ACT_ID = Activity ID
MR_ID = Material ID
MD_Q = Demand Quantity

Materials
MR_ID = Material ID
PR_ID = Project ID
MR_MinO = Supplier min order quantity
MR_MaxO = Supplier max order quantity
MR_FOP1 = Ordering Period 1
MR_FOP2 = Ordering Period 2
MR_FOP3 = Ordering Period 3
MR_FOP4 = Ordering Period 4
MR_DAD = Delivery average delay
MR_STC = Storage Category

Permissible Storage Periods
ACT_ID1 = ID of period starting activity
ACT_ID1 = ID of period ending activity
FL_ID = Floor ID
MR_Cat = materials category

Buildings
BL_ID = Building ID
PR_ID = Project ID
BL_Xmin = Building min X Coordinate
BL_Ymin = Building min Y Coordinate
BL_Xmax = Building max X Coordinate
BL_Ymax = Building max Y Coordinate
BL_HX = X Coordinate of material hoist
BL_HY = Y Coordinate of material hoist
ST_ID = Stage ID of construction start

Floors
FL_ID = Floor ID
BL_ID = Building ID
FL_Elev = Floor elevation
FL_GID = Global ID in IFC Model

Building Elements and Rooms
ERM_ID = Element/Room ID
FL_ID = Floor ID
ERM_TY = Type
ERM_Name = Element/Room Name
ERM_Xmin = Min X Coordinate
ERM_Ymin = Min Y Coordinate
ERM_Zmin = Min Z Coordinate
ERM_Xmax = Max X Coordinate
ERM_Ymax = Max Y Coordinate
ERM_Zmax = Max Z Coordinate
ERM_Area = Room Area
ERM_GID = Global ID in in IFC Model

Exterior Workspaces
ACT_ID = Activity ID
EW_TY = type: zone or facility
FC_ID = Facility ID
EW_Xmin = Min X Coordinate
EW_Xmax = Max X Coordinate
EW_Ymin = Min Y Coordinate
EW_Ymax = Max Y Coordinate

Interior Workspaces
ACT_ID = Activity ID
ERM_ID = Element/Room ID
IW_Area = Required Area

Partitioning Activities
ACT_ID = Activity ID
FL_ID = Floor ID

Rooms Creation Activities
ACT_ID = Activity ID
ERM_ID = Element/Room ID

Table 6.2 Attributes of Logistics Data Tables

Construction Stages	Facilities Zone Constraints
ST_ID = Stage ID	FC_ID = Facility ID
PR_ID = Project ID	ST_ID = Stage ID
ST_Start = Stage start time	ZC_TY = Type (Inclusion or Exclusion)
ST_Finish = Stage finish time	ZC_Xmin = Zone min X Coordinate
Site Facilities	ZC_Ymin = Zone min Y Coordinate
FC_ID = Facility ID	ZC_Xmax = Zone max X Coordinate
ST_ID1 = ID of existence first stage	ZC_Ymax = Zone max Y Coordinate
ST_ID2 = ID of existence first stage	Material Zone Constraints
FC_TY = Facility Type	MR_ID = Material ID
FC_Lx = Length in X direction	ST_ID = Stage ID
FC_Ly = Length in Y direction	ZC_TY = Type (Inclusion or Exclusion)
FC_X = X Coordinate of facility (fixed type)	ZC_Xmin = Zone min X Coordinate
FC_Y = Y Coordinate of facility (fixed type)	ZC_Ymin = Zone min Y Coordinate
FC_RCF = Fixed relocation cost	ZC_Xmax = Zone max X Coordinate
FC_RCV = Variable relocation cost	ZC_Ymax = Zone max Y Coordinate
Facilities Travel Cost Rates (F-F)	Material Purchase Cost Rates
FC_ID1 = ID of first facility	MR_ID = Material ID
FC_ID2 = ID of second facility	ST_ID = Stage ID
ST_ID = Stage ID	MPC_Q1 = Price range starting quantity
TCR_R = Travel cost rate	MPC_Q2 = Price range ending quantity
Facilities-Buildings Travel Cost Rates (F-B)	MPC_R = Purchase cost rate
FC_ID = Facility ID	Material Delivery Costs
BL_ID = Building ID	MR_ID = Material ID
ST_ID = Stage ID	ST_ID = Stage ID
TCR_R = Travel cost rate	MDC_Q1 = Delivery range starting quantity
Facilities Distance Constraints (F-F)	MDC_Q2 = Delivery range ending quantity
FC_ID1 = ID of first facility	MDC_C = Delivery cost
FC_ID2 = ID of second facility	Material Storage Footprints
ST_ID = Stage ID	MR_ID = Material ID
DC_TY = Type (min or max distance)	MFT_Q1 = Footprint range starting quantity
DC_Val = distance value	MFT_Q2 = Footprint range ending quantity
Facilities-Buildings Distance Constraints (F-B)	MFT_Lx = Footprint length in X direction
FC_ID = Facility ID	MFT_Ly = Footprint length in Y direction
BL_ID = Building ID	Material Handling Crew
ST_ID = Stage ID	MR_ID = Material ID
DC_TY = Type (min or max distance)	MHC_TY = Type (vertical or horizontal)
DC_Val = distance value	MHC_Name = Crew name
Facilities-Material Distance Constraints (F-M)	MHC_Speed = Crew Speed
FC_ID = Facility ID	MHC_Q = Handling quantity
MR_ID = Material ID	MHC_C = Crew Hourly Cost
ST_ID = Stage ID	
DC_TY = Type (min or max distance)	
DC_Val = distance value	

6.5 User Interface Module

The purpose of this interface module is to facilitate interactive and seamless input of all necessary project data and reporting generated optimal logistics plans. This module is designed to implement its functions in two main phases: (1) an input phase to obtain, integrate, and store project spatial, schedule, logistics, and optimization data; and (2) an output phase to facilitate the retrieval, reporting and visualization of the generated optimal logistics plans. The developed graphical user interface module is implemented using Microsoft Foundation Classes (MFC) and Visual C++ programming language to benefit from their advanced capabilities in object-oriented modeling and interaction with other software applications (e.g. IFCEngine, relational databases, and NSGA-II). The relationships and interactions between the input and output phases in the present module and the other modules of the system are illustrated in Figure 6.1. The following two subsections provide a detailed description of the flow of data during the input and output phases for the application example presented in Section 5.6.

6.5.1 Input Phase

The input phase is designed to facilitate and simplify the process of inputting all required data for construction logistics planning and optimization. To accomplish this, a set of interactive graphical user interface forms and controls are implemented to guide construction planners in entering the necessary data in six main steps:

Step (1) Create or open a project file: the planner selects in the first form to either create a new file or open an existing one for the analyzed construction project, as shown in Figure

6.5. The user interface is designed to enable AMCLOS users to save all project defined data during any time of the input phase in binary format files, which can be reloaded for later utilization in future sessions of the system.

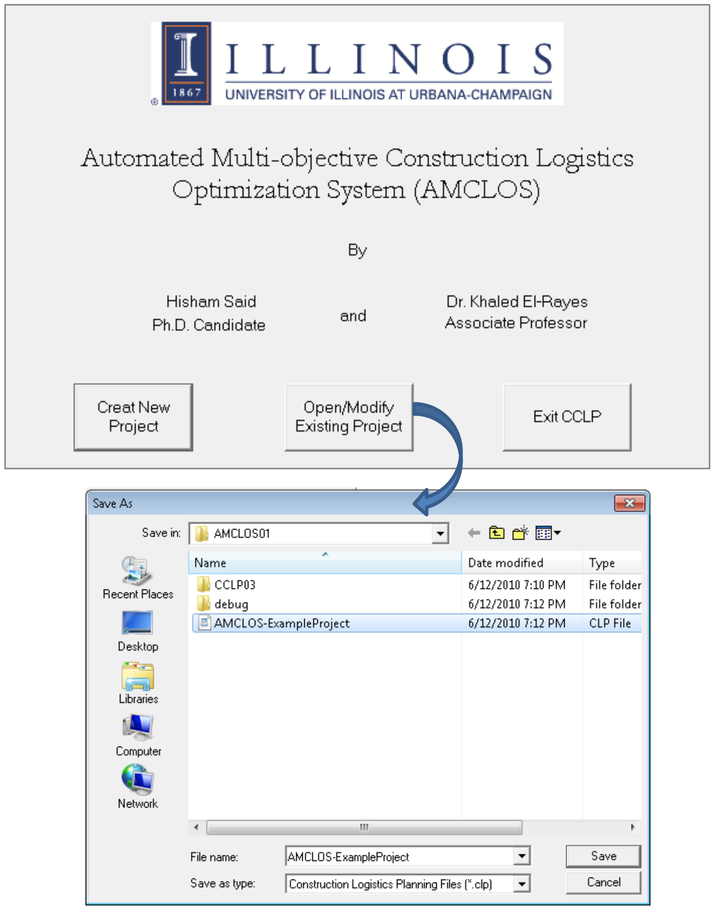


Figure 6.5 AMCLOS Information and Main Options Form

Step (2) Input Project Spatial Data: The project spatial data form is designed to facilitate the selection of the IFC file of project building information model and displaying the retrieved data of site boundaries, project buildings, building floors, building elements, and rooms, as shown in Figure 6.6. The present user interface module enables the selection of IFC files of more than one building in the same project, to retrieve: (1) site boundary coordinates, (2) buildings footprint coordinates, (3) buildings floors, (4) buildings elements (e.g. columns, walls, etc.), and (5) buildings rooms. Summarized and detailed views of these retrieved spatial data are displayed to the users for review and validation purposes.

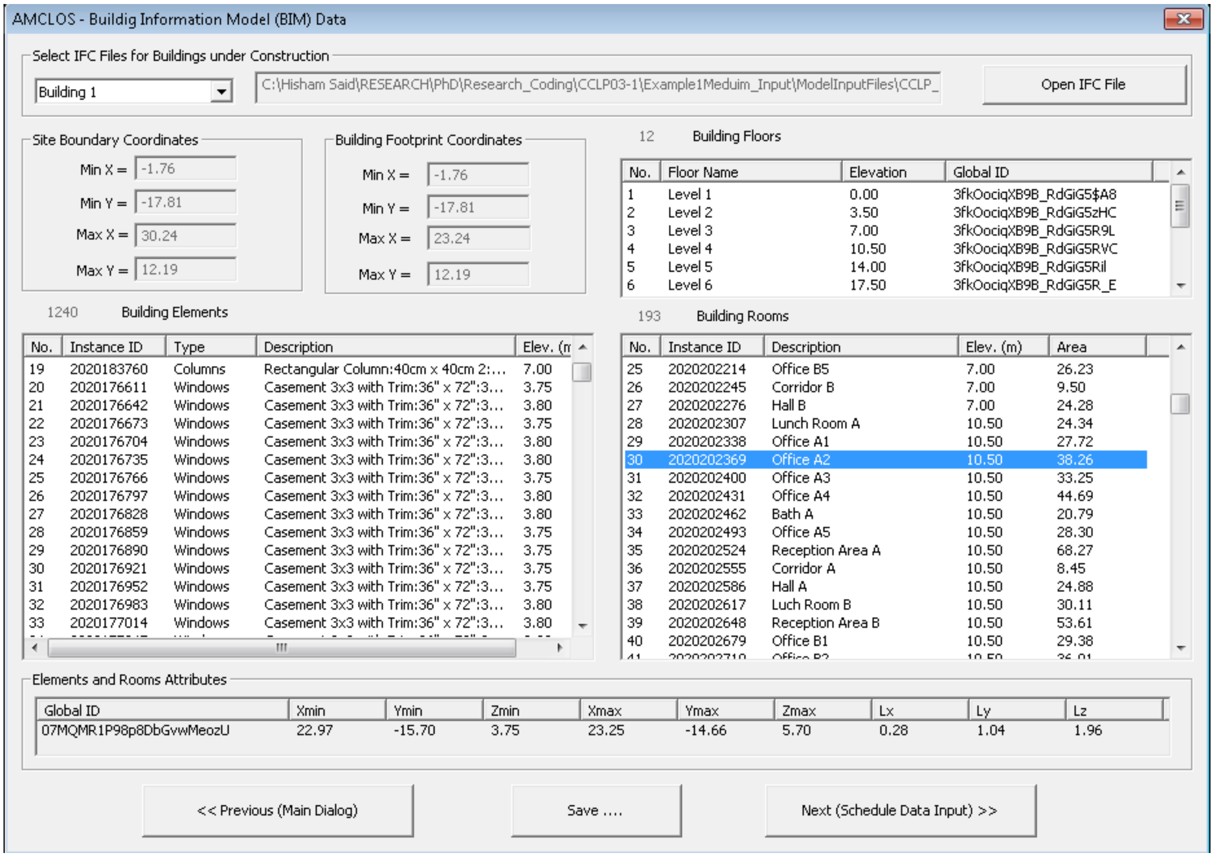


Figure 6.6 Project Spatial Data Form

<u>Step (3) Input Project Schedule Data</u>: This step enables AMCLOS users to select a Microsoft Project file that is saved in a database (mdb) format, as shown in Figure 6.7, in order to retrieve: (1) the list of construction activities, (2) the relationships between these activities, (3) utilized construction materials; and (4) the demand for these materials by each activity. Interactive controls are implemented in the schedule data form to display relationships and material demand of any selected activity as well as demanding activities for a selected material.

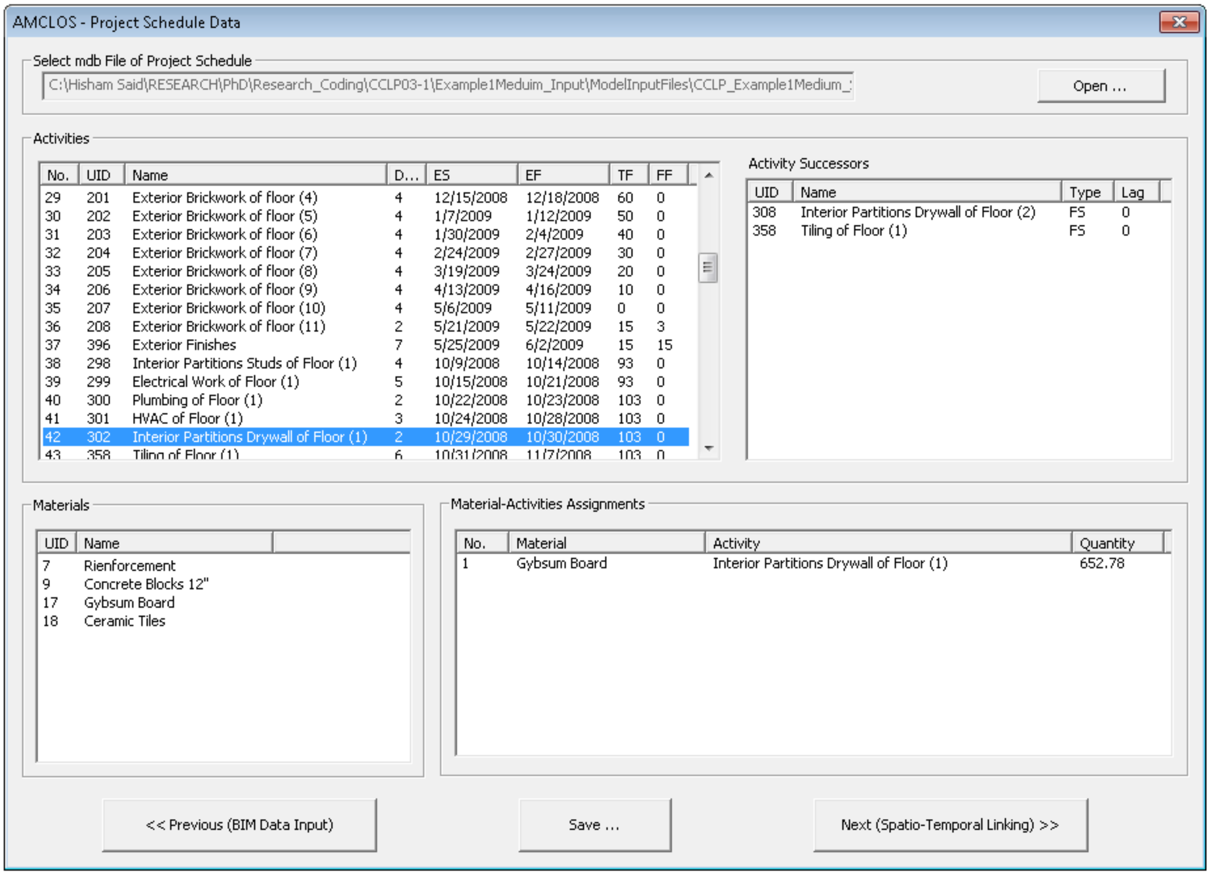


Figure 6.7 Project Schedule Data Form

Step (4) Define Spatio-Temporal Linking Data: Four types of relationships are defined between construction activities and each building's floors and rooms, as shown in Figure 6.8: (1) the creation activity of each building room; (2) the partitioning activity of each building floor; (3) required areas and locations of interior activities workspaces in the defined building rooms, defined in step 3, and workspaces centroid of exterior activities; and (4) starting and ending activities of storage permissible periods of each material in every floor. In order to support construction planners in defining this large set of data, AMCLOS enables them to:

(1) select construction activities, building floors, and rooms for their spatio-temporal linkage using popup forms with readily populated lists, as shown in Figure 6.9; (2) import these linking data that are stored in commonly used formats, such as spreadsheets; and (3) classify construction materials into categories that share the same permissible storage periods.

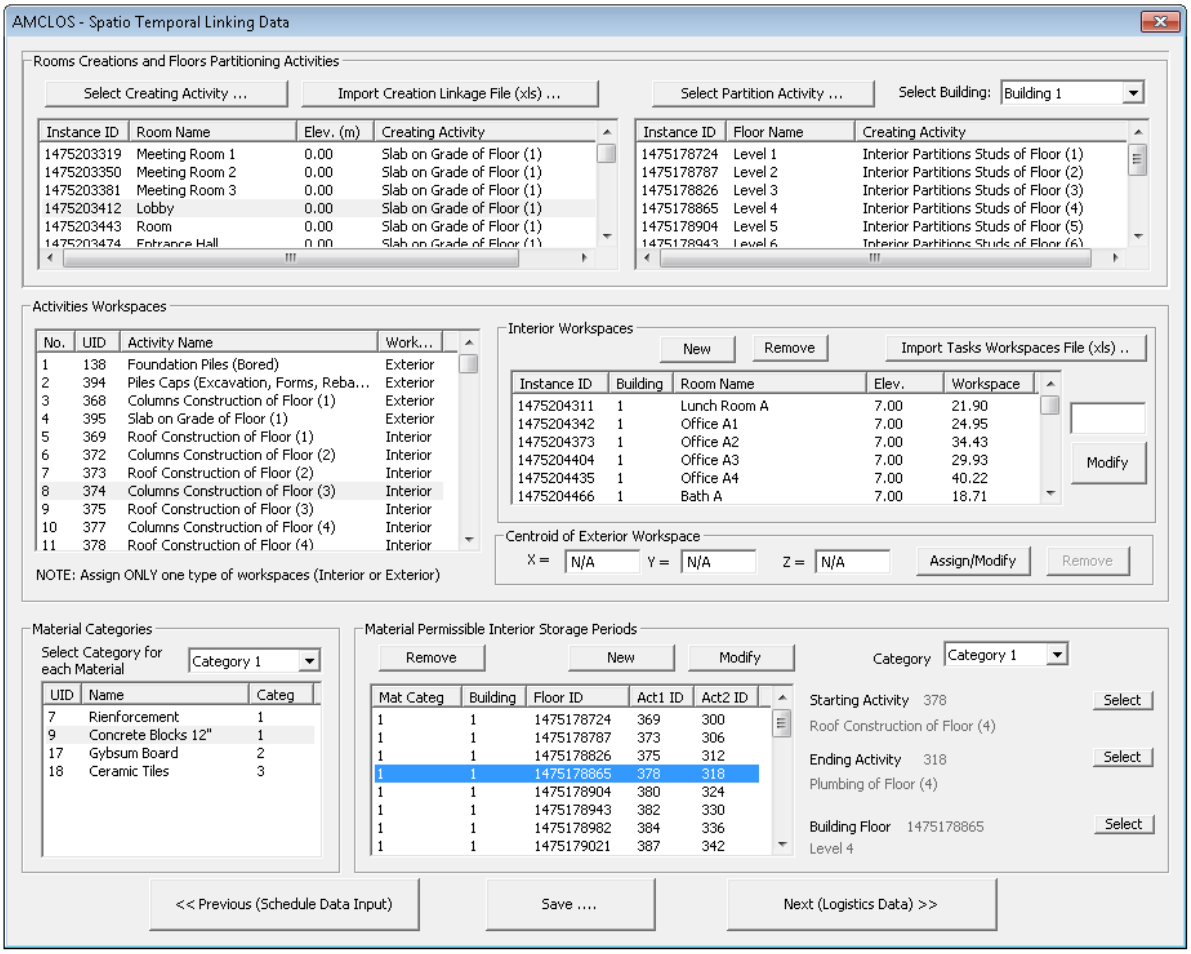
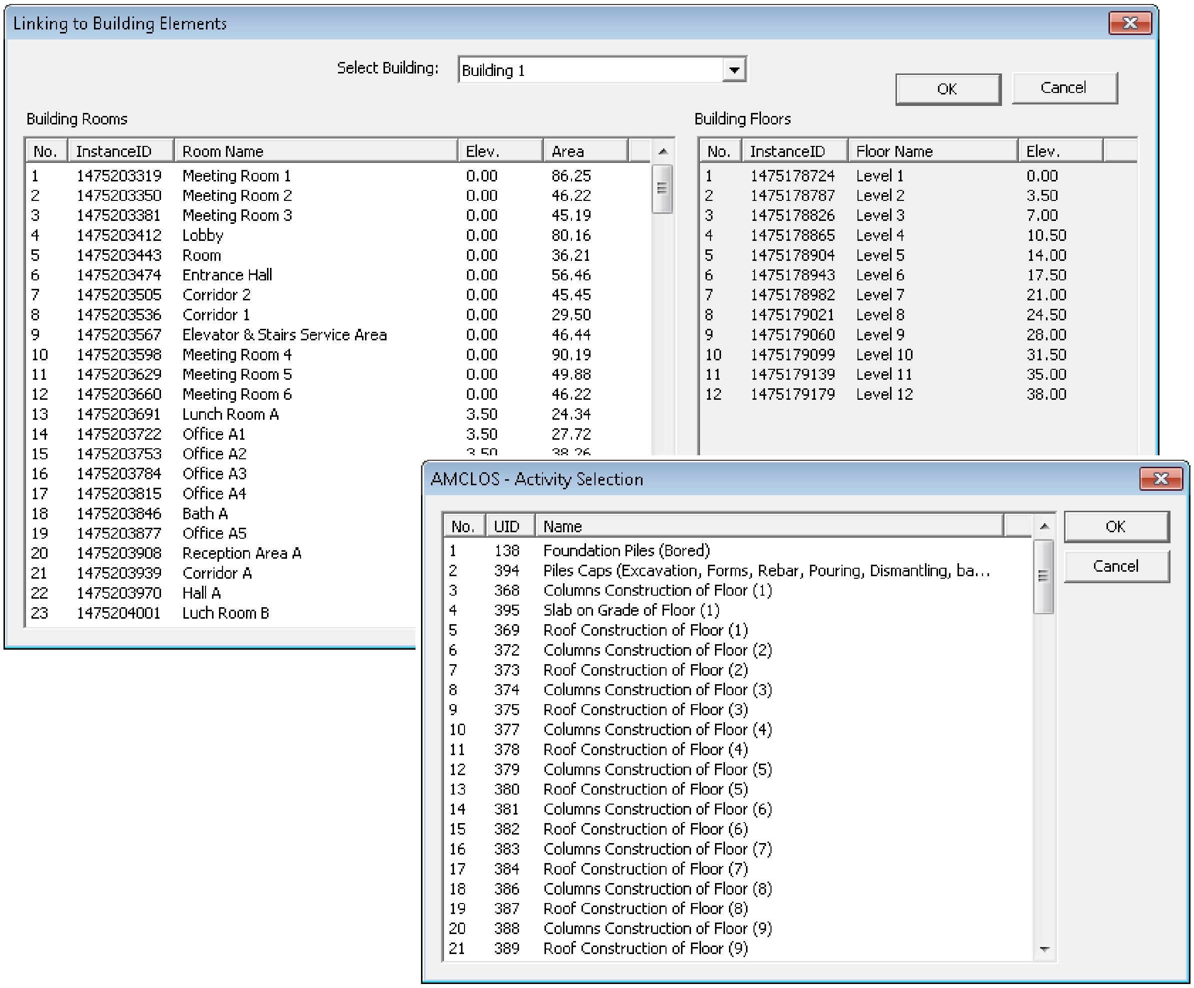


Figure 6.8 Spatio-Temporal Linking Form



Linking to Building Elements

Select Building: Building 1

OK Cancel

Building Rooms

No.	InstanceID	Room Name	Elev.	Area
1	1475203319	Meeting Room 1	0.00	86.25
2	1475203350	Meeting Room 2	0.00	46.22
3	1475203381	Meeting Room 3	0.00	45.19
4	1475203412	Lobby	0.00	80.16
5	1475203443	Room	0.00	36.21
6	1475203474	Entrance Hall	0.00	56.46
7	1475203505	Corridor 2	0.00	45.45
8	1475203536	Corridor 1	0.00	29.50
9	1475203567	Elevator & Stairs Service Area	0.00	46.44
10	1475203598	Meeting Room 4	0.00	90.19
11	1475203629	Meeting Room 5	0.00	49.88
12	1475203660	Meeting Room 6	0.00	46.22
13	1475203691	Lunch Room A	3.50	24.34
14	1475203722	Office A1	3.50	27.72
15	1475203753	Office A2		
16	1475203784	Office A3		
17	1475203815	Office A4		
18	1475203846	Bath A		
19	1475203877	Office A5		
20	1475203908	Reception Area A		
21	1475203939	Corridor A		
22	1475203970	Hall A		
23	1475204001	Luch Room B		

Building Floors

No.	InstanceID	Floor Name	Elev.
1	1475178724	Level 1	0.00
2	1475178787	Level 2	3.50
3	1475178826	Level 3	7.00
4	1475178865	Level 4	10.50
5	1475178904	Level 5	14.00
6	1475178943	Level 6	17.50
7	1475178982	Level 7	21.00
8	1475179021	Level 8	24.50
9	1475179060	Level 9	28.00
10	1475179099	Level 10	31.50
11	1475179139	Level 11	35.00
12	1475179179	Level 12	38.00

AMCLOS - Activity Selection

OK Cancel

No.	UID	Name
1	138	Foundation Piles (Bored)
2	394	Piles Caps (Excavation, Forms, Rebar, Pouring, Dismantling, ba...
3	368	Columns Construction of Floor (1)
4	395	Slab on Grade of Floor (1)
5	369	Roof Construction of Floor (1)
6	372	Columns Construction of Floor (2)
7	373	Roof Construction of Floor (2)
8	374	Columns Construction of Floor (3)
9	375	Roof Construction of Floor (3)
10	377	Columns Construction of Floor (4)
11	378	Roof Construction of Floor (4)
12	379	Columns Construction of Floor (5)
13	380	Roof Construction of Floor (5)
14	381	Columns Construction of Floor (6)
15	382	Roof Construction of Floor (6)
16	383	Columns Construction of Floor (7)
17	384	Roof Construction of Floor (7)
18	386	Columns Construction of Floor (8)
19	387	Roof Construction of Floor (8)
20	388	Columns Construction of Floor (9)
21	389	Roof Construction of Floor (9)

Figure 6.9 Selection Forms of Activities, Buildings Rooms, and Floors

<u>Step (5) Input Logistics Data</u>: AMCLOS users are asked during this step of the input phase to provide project logistics data using three forms, as shown in Figures 6.10 through 6.12. The first forms is designed to obtain project general parameters, planning stages, material storage footprint schedules, distance constraints between material storage areas and buildings under construction, material purchase cost rates, material delivery costs, and handling crews (e.g. horizontal and vertical), as shown in Figure 6.10. The second form enables planners to define materials supply data, material zone constraints, locations of material hoists in each building, and construction starting stage of each building, as shown in Figure 6.11. The third form is used to define construction temporary facilities data, including their spatial representation and imposed geometric constraints (e.g. distance and zone constraints) with respect to other facilities, buildings, and material storage areas, as shown in Figure 6.12.

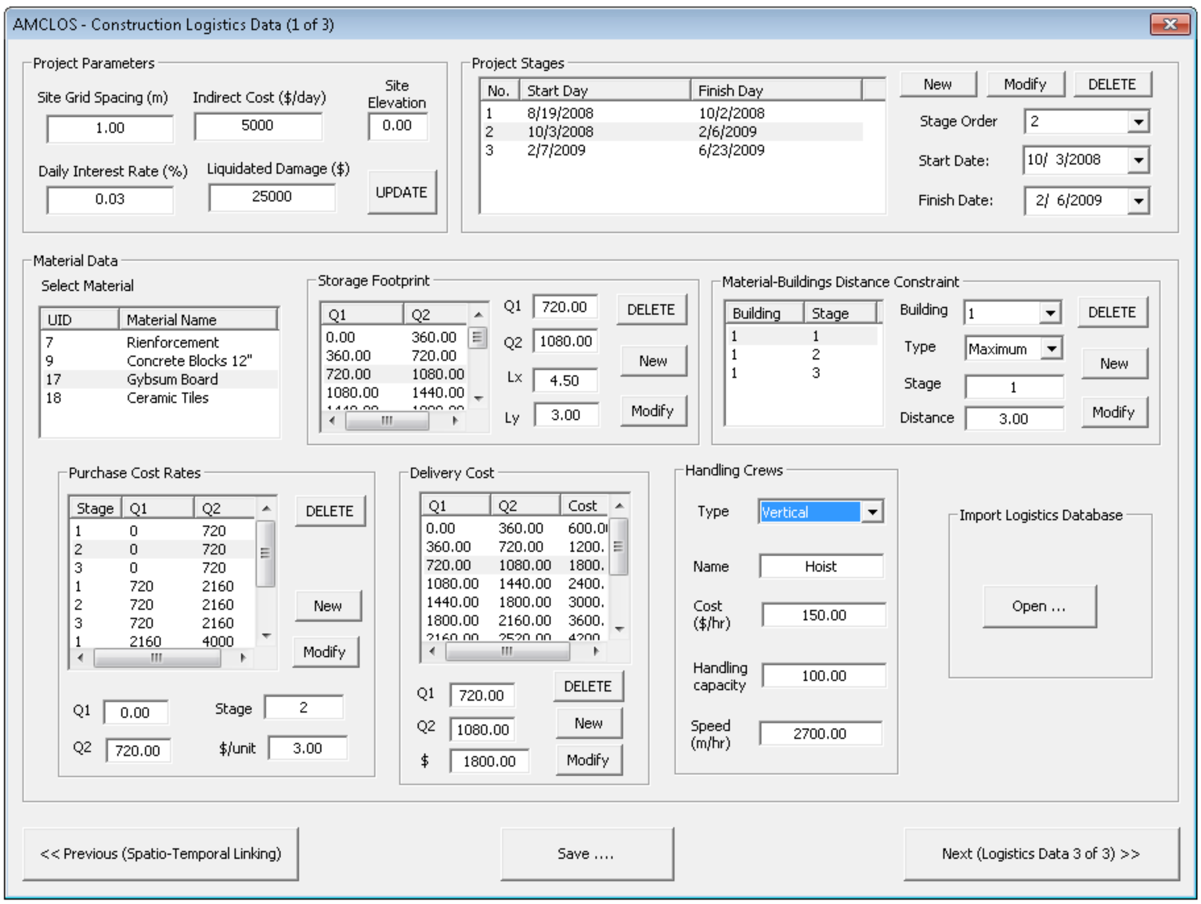


Figure 6.10 Construction Logistics Data Form 1

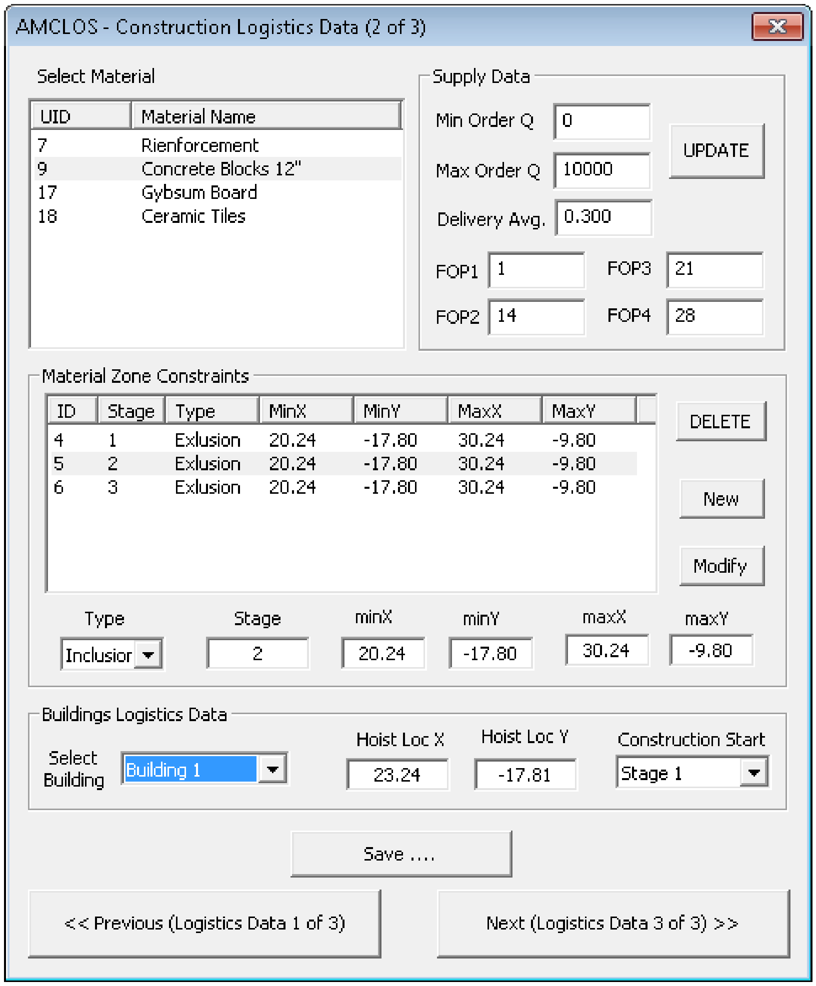


Figure 6.11 Construction Logistics Data Form 2

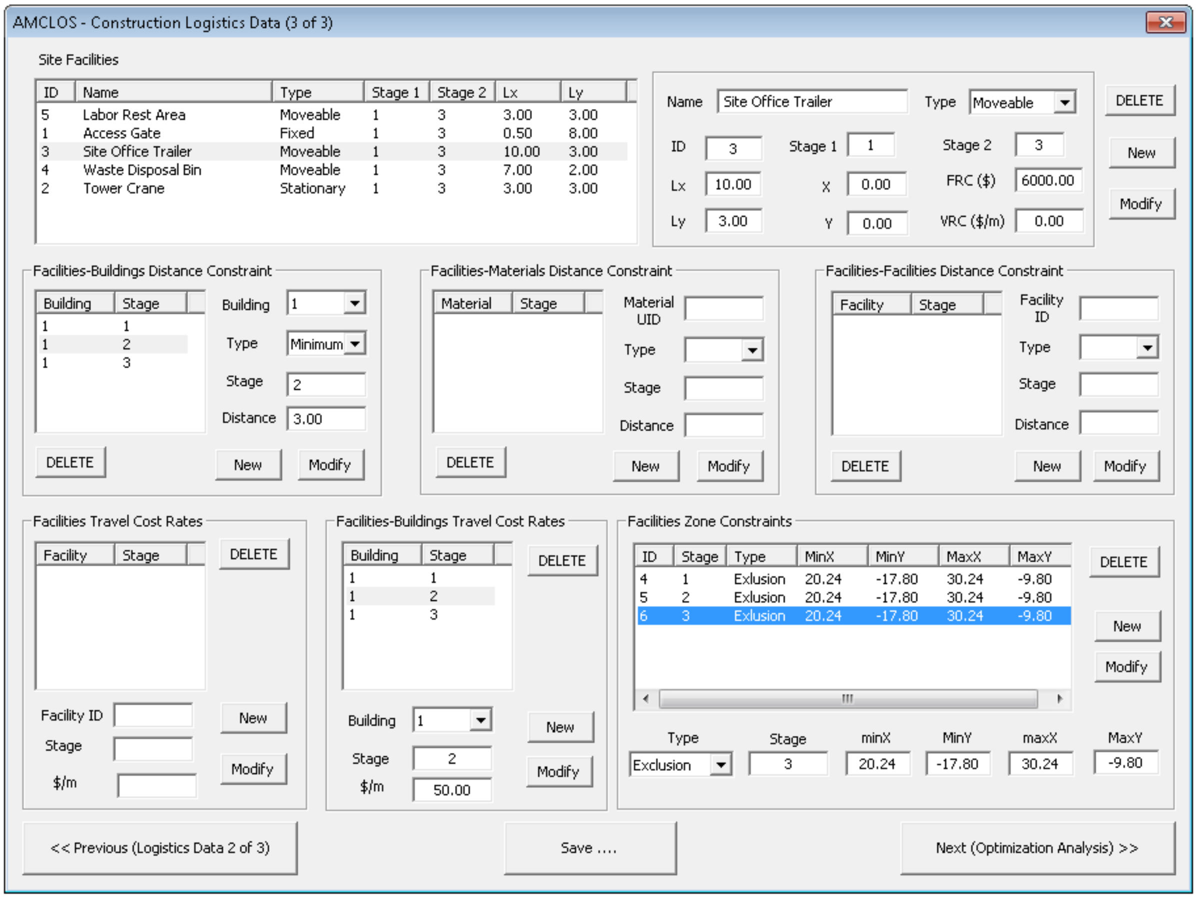


Figure 6.12 Construction Logistics Data Form 3

Step (6) Specify GA Optimization Parameters: The last step of the input phase of the present user interface module is designed to facilitate the input of the genetic algorithm parameters needed to initiate the multi-objective optimization model, as shown in Figure 6.13. The main parameters that are captured in this step include: (1) the number of genetic algorithms generations; (2) the population size; (3) the type and probability of crossover operator (4) the mutation probabilities for both binary and real coded decision variables; and (6) the random seed used to create the first population of solutions (Deb et al. 2001). The values of these parameters are specified based on the number of decision variables (Reed et al. 2003, Deb 2001), which depends on the number of project materials, stages, activities, and temporary facilities. The multi-objective optimization analysis is then invoked by clicking the "optimize" button in the GA Optimization form, as shown in Figure 6.13. All generated solutions at the end of the optimization analysis are retrieved and reported in the output phase of the user interface module. In addition, the results of a previous optimization analysis can be uploaded and reviewed by clicking the "open results file" button.

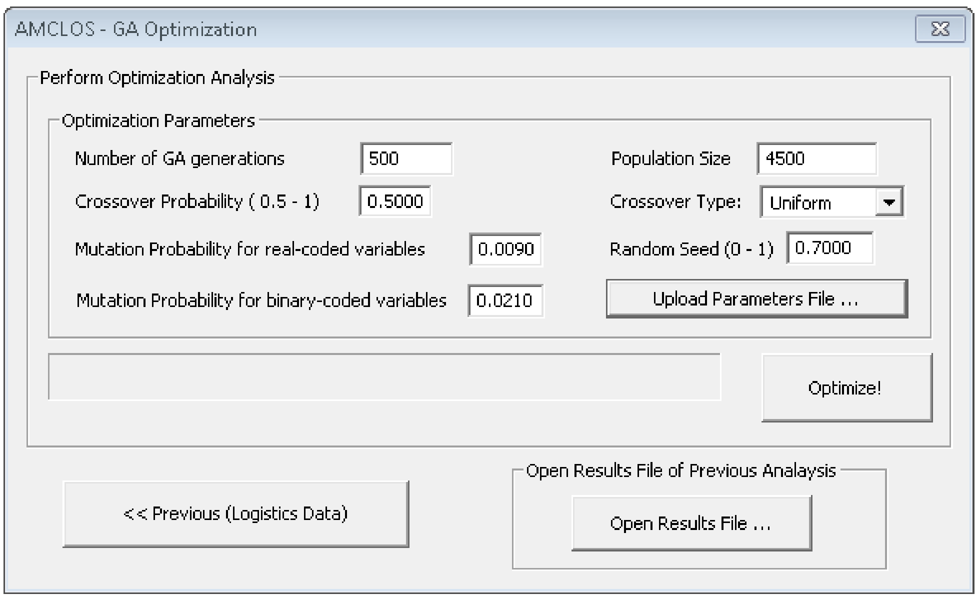


Figure 6.13 GA Optimization Analysis Form

6.5.2 Output Phase

The output phase of the present user interface module is designed to enable the retrieval and visualization of generated optimal tradeoffs between construction logistics costs and project schedule criticality, as shown in Figure 6.14. The user interface module reports AMCLOS optimization results in this output phase by: (1) displaying a summarized material procurement plan, material storage plan, dynamic site layout plan, and scheduling of noncritical facilities of any optimal tradeoff solution selected by the planner; (2) plotting all generated optimal solution to graphically demonstrate the non-dominated tradeoff between minimizing logistics costs and schedule criticality; and (3) exporting a detailed logistics plan of a selected optimal solution for further review and implementation by construction planners.

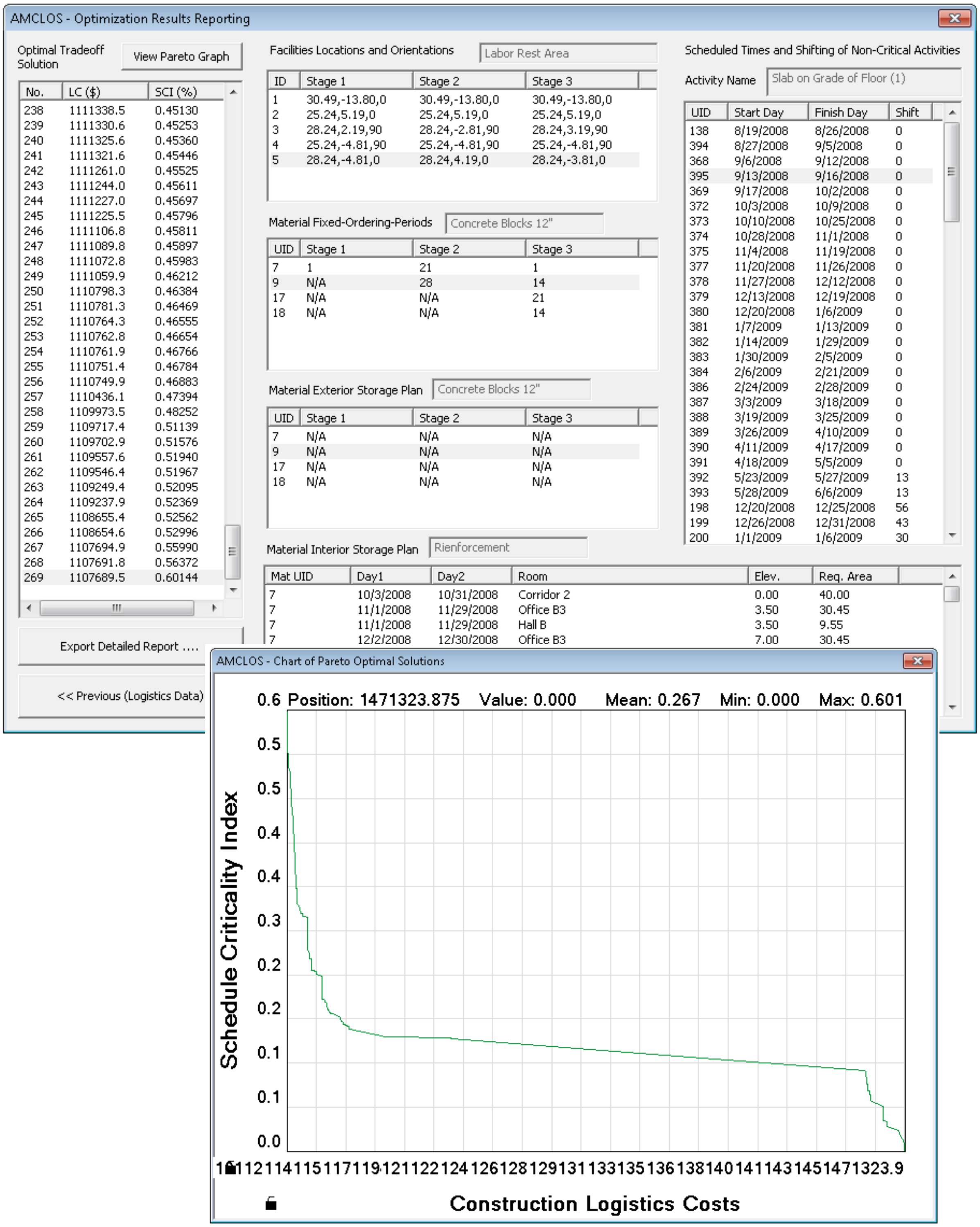


Figure 6.14 AMCLOS Optimization Results Forms

6.6 Summary

This chapter presented the development of a prototype automated multi-objective construction logistics optimization system (AMCLOS) that facilitates the optimization of material logistics and site layout planning. The developed system is designed to help construction planners in defining and integrating project spatial, schedule, and logistics input data in order to generate optimal logistics plans that present non-dominated tradeoffs between minimizing logistics costs and schedule criticality. The system is developed in four main modules: (1) site spatial data retrieval module; (2) schedule data retrieval module; (3) relational database module; and (4) graphical user interface module. The site spatial data retrieval module facilitates the automated retrieval of site exterior dimensions and building geometric attributes (building footprint, floors, and rooms) from existing IFC-Based Building Information Models of the project. The schedule data retrieval module is designed to obtain the list of construction activities, their relationships, construction materials, and activities material demand from schedule database files that are exported from Microsoft Project. The relational database module is designed to store and integrate project spatial, temporal, and logistics input data considering their interdependencies in order to eliminate data inconsistencies. The user interface module facilitates data input and reporting of the generated optimal material logistics plans.

CHAPTER 7
CONSTRUCTION SITE SECURITY PLANNING MODEL

7.1 Introduction

The objective of this chapter is to present the development of a multi-objective optimization framework for planning construction site layouts and site security systems for critical infrastructure projects. The framework is designed to help contractors and security officers in generating dynamic optimal site layouts and security systems that minimize both security risks and site costs over the construction period. A multi-objective Genetic Algorithm (GA) is incorporated into the present framework to enable optimal tradeoff analysis between these two critical optimization objectives. The present framework is formulated and devised to enable: (1) modeling the construction site as a dynamic security system that includes security targets, boundaries, countermeasures, and potential attackers as well as modeling the dynamic construction site space availability and needs that change over time; (2) modeling and optimizing the use of security lighting systems on construction sites; (3) quantifying the impact of the implemented security and site layout measures on the performance of the security system using newly developed metrics and methodologies; and (4) generating optimal tradeoffs between the optimization objectives of minimizing security risks and minimizing overall site cost. As shown in Figure 7.1, the present framework is developed in four main phases: (1) risk identification and system modeling phase to identify the components of construction site security system and the site layout planning; (2) security lighting optimization phase to optimize the design of lighting systems on construction sites for critical infrastructure projects; (3) security-cost optimization phase to generate optimal site security systems that provide optimal tradeoffs between minimizing the security risks and minimizing the overall site cost; and (4) performance evaluation phase to test and analyze the performance of the proposed framework. The following sections describe these four development stages. Lighting optimization is performed in a separate phase because it involves a set of interdependent decision variables (such as luminaire type and pole height) that significantly impact lighting performance and cost (IESNA 2000). Preliminary experiments were conducted to evaluate the incorporation of security lighting decision variables in the optimization of the whole security system. These experiments showed that optimizing the lighting system in a separate phase provided better performance in terms of computational time and solutions quality. The following sections describe the four development stages of the present framework.

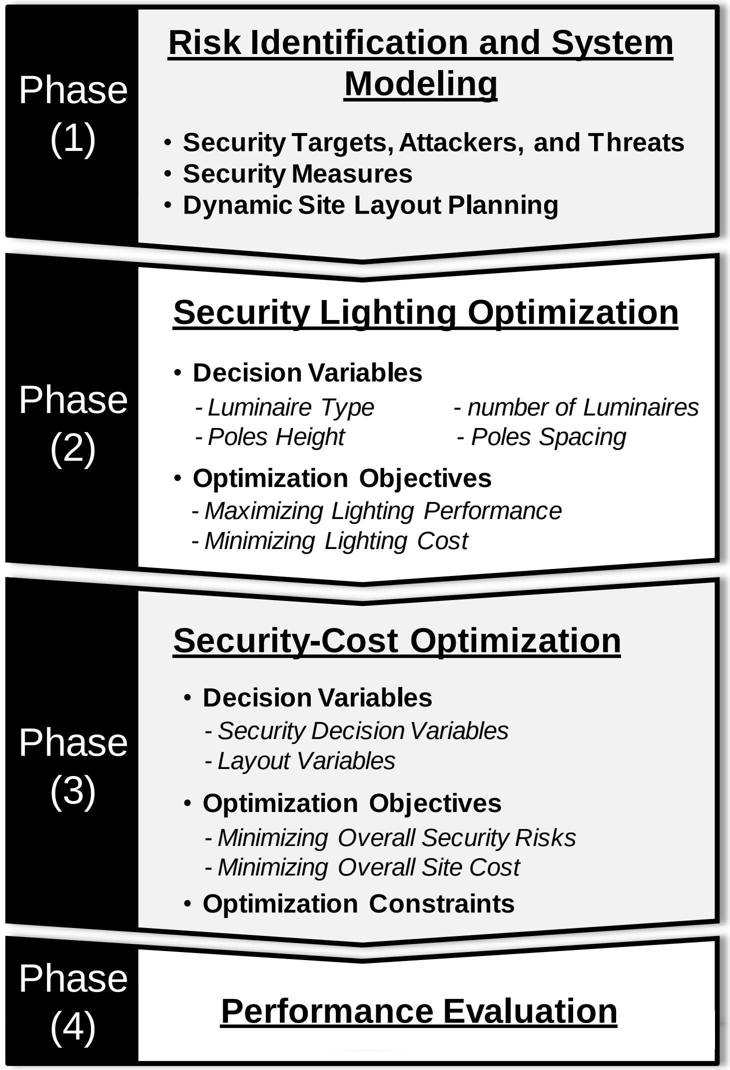


Figure 7.1 Framework for Optimizing the Planning of Construction Site Layout and Security Systems for Critical Infrastructure Projects

7.2 Risk Identification and System Modeling

The main purpose of this phase is to develop a model of the construction site security system that considers and represents the identified security threats, targets and attackers. This risk identification analysis is often performed to assess security threats by identifying site targets and possible attackers (Strutt et al 1995). Site targets include the critical facility under construction, site office trailers that contain sensitive information, and/or storage areas of classified equipment or material. Possible attackers include individuals or groups that aim to acquire or destroy onsite critical assets, such as information, materials, or equipments (CII 2005; Matthews et al 2006). As shown in Figure 7.2, a security threat is identified between each pair of attackers (*a*) and targets (*r*) in each construction stage (*t*) by estimating two main attributes: probability of occurrence ($P_{a,r}^{t}$) and consequences ($C_{a,r}^{t}$).Project security officers can represent the consequences of successful attacks using dimensionless indices (between 0 and 1), where higher values indicate more severe consequences. Probabilities and consequences of potential attacks as well as other threat data such as attackers intrusion speed and action time of response forces can be obtained from risk identification analysis that are performed by Federal agencies (DCID 1995 and DCID 2002) or by utilizing risk and vulnerability assessment techniques described in NIST and CII reports (CII 2005, NIST 2004-a and 2004-b).

The main purpose of the developed construction security model is to deploy security countermeasures in a way that collectively achieve the following four main security functions: deterrence, detection, delay, and detainment (Tarr 1992). The first function is to deter potential opponents and decrease their tendency of attack by applying fences, lighting, and natural surveillance. It should be noted that the layout of site facilities affects greatly the natural surveillance around security targets. The second function is to detect any attacker's breach by applying intrusion detection systems in the fences of targets or the whole site. Once an attacker is detected, the third function of the system is to delay the attacker by applying fences and long distances between site fence and targets. The fourth function is to detain and neutralize attackers before achieving their mission by having a response force that can be either an onsite force or local law enforcement patrol.

In the present model, the aforementioned functions of the construction security system are accomplished by deploying various security countermeasures. As shown in Figure 7.2, these countermeasures are grouped and organized in three main layers on the construction site: (1) site fence or the outer layer, (2) site grounds or the intermediate layer, and (3) target fence or the inner layer. Security countermeasures are implemented over these security layers to enable the quantification of the effectiveness of the whole security system (Fennelly 2004, Hicks et al 1998). As shown in Figure 7.2, the site and target fences layers are composed of security fences, intrusion detection systems, and fence lighting, while the site grounds layer provides security using area lighting, response forces and natural surveillance (CII 2005).

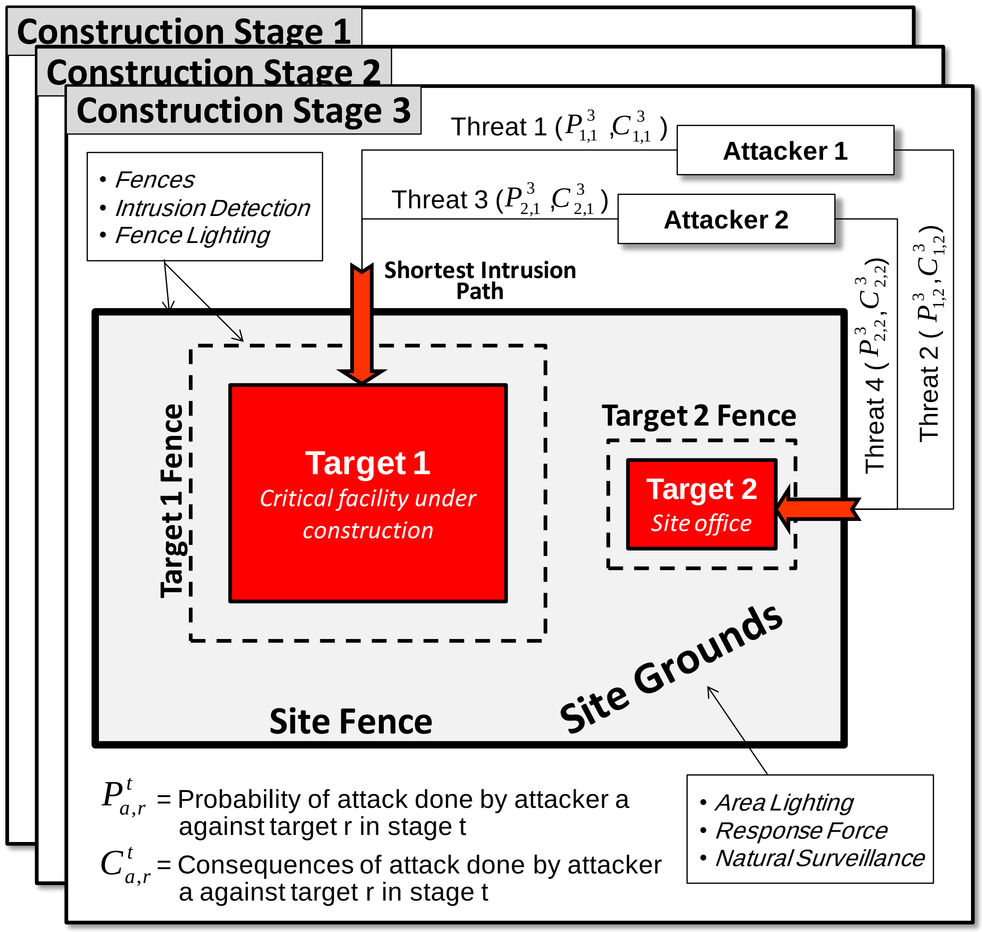


Figure 7.2 Representation of Site Security System and Space

The layout of construction site facilities is dynamically planned to account for changing space needs and security threats. Construction site facilities are classified into three categories: (1) fixed facilities that are used to represent structures under construction; (2) moveable facilities to represent temporary construction facilities that can be relocated with additional cost such as storage and fabrication areas; and (3) stationary facilities to represent facilities that cannot be relocated because of the required significant time, cost, and effort such as tower cranes (El-Rayes and Said 2009; Zouein and Tommelein 1999). As shown in Figure 7.2, these site facilities and fence are represented in the present model using 2D rectangular shapes. The model is designed to dynamically position all temporary facilities (i.e. moveable and stationary) and relocating moveable facilities in every stage of the project duration. It should be noted that security targets and measures are assumed to be stationary facilities because of the significant cost and time that are required to relocate them. For example, if the site office contains sensitive compartmented information and is assessed as a security target, it is classified as a stationary facility to exclude the infeasible scenario of relocating it and its surrounding security fence.

7.3 Security Lighting Optimization

The main purpose of this phase is to model and optimize security lighting systems to generate a list of optimal lighting options to be considered in the next phase of security-cost optimization phase. Lighting systems can be used on constructions site to provide adequate illuminance to act as a deterrent to attackers and help in their detainment (Boyce 2003, CII 2005). As shown in Figure 7.3, site security lighting includes two main components: (1) area lighting system; and (2) fence lighting system. Area lighting system is utilized to illuminate construction site grounds while fence lighting system is used to shed additional lighting on the security fences of targets and construction sites. Area and fence lighting systems are analyzed separately to comply with the Illuminating Engineering Society of North America (IESNA) requirements that recommend different illumination level for each of them (IESNA 2000). The area lighting system can be implemented as a grid of pole-mounted luminaires that can be used to cover the entire construction site. The fence lighting system is a line of pole-mounted luminaires that are located along security fences to illuminate the area on both sides of the fence with a specified fence lighting width (*FLW*) determined by security officers. The following subsections describe the decision variables and optimization objectives considered in the design of these security lighting systems.

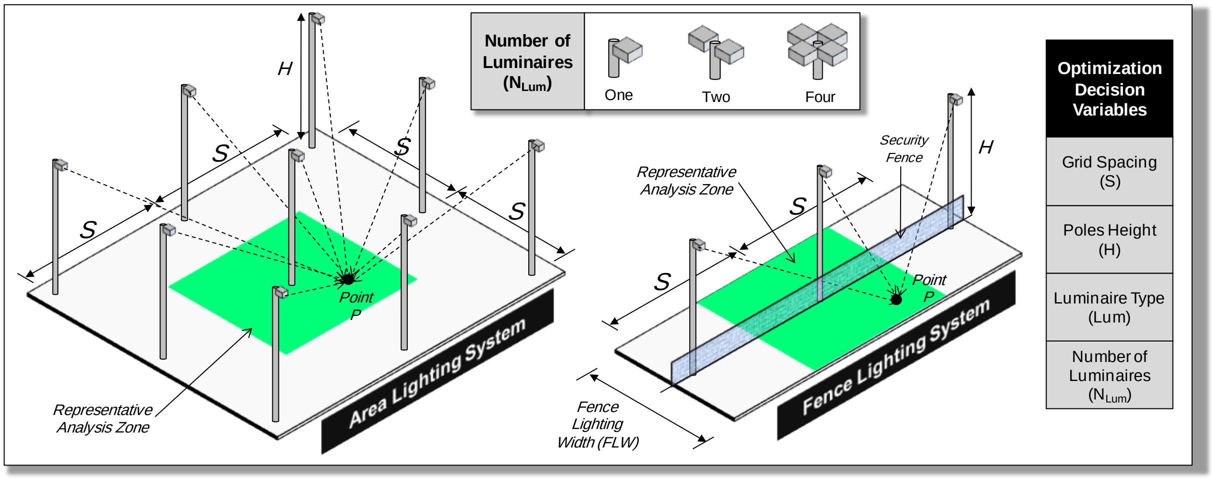


Figure 7.3 Optimization of Area and Fence Lighting Systems

7.3.1 Lighting Decision Variables

The design of security lighting systems needs to identify four main decision variables for area and fence lighting systems: (1) grid spacing of light poles, (2) poles height, (3) luminaires type, and (4) and number of luminaires per pole, as shown in Figure 7.3. The average illuminance level on site can be increased by: (1) reducing the spacing *S* between light poles which increases the overlap between the light cones of adjacent poles; (2) decreasing the height of light poles which reduces the vertical distance between the lighting source (luminaires) and the ground; (3) selecting luminaire types that provide high lighting intensity; and (4) increasing the number of luminaires per pole that can be designed to include 1, 2, or 4 luminaires, as shown in Figure 7.3.

7.3.2 Lighting Objective Functions

The present model is designed to optimize the tradeoff between the two important design objectives of maximizing the lighting performance and minimizing the lighting system cost. As shown in Figure 7.3, the lighting system optimization is performed over a representative analysis zone to reduce the computational overhead of the present framework. A representative zone of the area lighting system is a lighting grid cell under one light pole (i.e. $area = S \times S$) that is illuminated by the adjacent nine light poles (i.e. $K = 9$). On the other hand, a representative zone of the fence lighting system is a lighting grid cell under one light pole (i.e. $area = S \times FLW$) that is illuminated by the adjacent three light poles (i.e. $K = 3$), as shown in Figure 7.3. The representative analysis zone is divided into identical grid cells in order to obtain a set of uniformly distributed calculation points (P). Accordingly, the lighting systems are optimized to accomplish the two important objectives of: (1) maximizing the lighting performance (*LGP*) over the representative zone; and (2) minimizing the lighting cost of the representative zone. It should be noted that the framework optimizes area and fence lighting systems separately and does not consider the mutual impacts between them in order to control the computational time and effort of the model and ensure its practicality. These mutual impacts between the two lighting systems can lead to slightly higher levels of illumination than those generated by the model.

First, the lighting performance (LGP) in the present model is designed to range from 0% to 100%. As shown in Equation 7.1, LGP depends on the average horizontal illuminance level (E_{avg}) in the representative analysis zone and the specified upper and lower bounds of average illuminance levels (E_U and E_L) that are recommended by security officers or specifications (IESNA 2000). For example, a lighting performance level of 100% can be achieved if the average horizontal illuminance level (E_{avg}) is equal to the specified upper bound of average illuminance level (E_U). On the other extreme, a lighting performance level of 0% can be encountered if the average horizontal illuminance level (E_{avg}) is equal to the specified lower bound of average illuminance level (E_L), as shown in Equation 7.1.

The average illuminance level (E_{avg}) in the representative analysis zone is calculated using Equation 7.2 as the average of the horizontal illuminance values (E_p) at all points P in the analysis zone. The horizontal illuminance level (E_p) at each point p is calculated by aggregating the horizontal illunminance levels reaching that point from the N_{Lum} luminaires that are positioned on top of each of the adjacent K poles (El-Rayes and Hyari 2005). As shown in Equation 7.3, the lighting system optimization is constrained by the allowable average-to-minimum illuminance ratio (EUR_{allow}) that is imposed by security specifications to facilitate easy detection of intruders (IESNA 2000). *EUR* is calculated as the ratio between the previously calculated average illuminance (Equation 7.2) and the minimum illuminance computed at any point in the representative analysis zone.

$$LGP = \frac{(E_{avg} - E_L)}{(E_U - E_L)} \times 100\% \tag{7.1}$$

$$E_{avg} = \frac{1}{P} \times \sum_{p=1}^{p} E_p = \frac{1}{P} \times \sum_{p=1}^{P} \sum_{k=1}^{K} \sum_{n=1}^{N_{Lum}} \frac{I_{pk}^{n} \times H}{\left(\sqrt{\Delta X_{pk}^{2} + \Delta Y_{pk}^{2} + H^{2}}\right)^{3}} \tag{7.2}$$

$$EUR = \frac{E_{avg}}{E_{\min}} \le EUR_{allow} \tag{7.3}$$

Where,

LGP = lighting performance;

E_{avg}, E_{min} = average and minimum horizontal illuminance in the analysis zone;

E_L, E_U = lower and upper bounds of required average illuminance levels;

P = number of calculation points in the analysis zone;

K = number of lighting poles under analysis, where K = 9 for area lighting analysis and K = 3 for fence lighting analysis;

N_{Lum} = number of luminaires that are positioned on top of the considered K poles;

E_p = horizontal illuminance reaching point P from the N_{Lum} luminaires on top of the considered K poles;

I_{pk}^{n} = lighting intensity directed from luminaire n on top of pole k toward calculation point p;

H = height of lighting poles;

$\Delta X_{pk}, \Delta Y_{pk}$ = horizontal distances in the x and y directions between pole k and point p; and

EUR, EUR_{allow} = calculated and allowable average-to-minimum illuminance ratio.

The second objective in security lighting optimization is minimizing the lighting cost over its usage period onsite including installation, energy, maintenance, and demobilization costs. Equation 7.4 is used to calculate the area unit cost for area lighting systems (LGC_{area}) and the length unit cost for fence lighting systems (LGC_{fence}) as the total of four main costs: (1) installation (LGC_1); (2) energy consumption (LGC_2); (3) operation and maintenance (LGC_3); and (4) demobilization costs (LGC_4). It should be noted that these costs are calculated for the lighting of the representative analysis area, which represents one light pole and N_{Lum} luminaires that are fixed on its top. Optimizing the lighting system involves tradeoffs between minimizing the cost and maximizing performance. For example, increasing the number of luminaires (N_{Lum}) enhances the security lighting performance (see Equation 7.2) but it will increase lighting costs (see Equations 5.6 through 5.9). Accordingly, the present framework is designed to generate a set of optimal lighting designs for both area and fence lighting systems that provide optimal tradeoffs between these two conflicting objectives.

$$LGC_{area} = \left(LGC_1 + LGC_2 + LGC_3 + LGC_4\right) / S_{area}^2 \tag{7.4}$$

$$LGC_{fence} = \left(LGC_1 + LGC_2 + LGC_3 + LGC_4\right) / S_{fence} \tag{7.5}$$

$$LGC_1 = N_{Lum} \times Cost_{Lum}^{inst} + Cost_{pole}^{inst} \tag{7.6}$$

$$LGC_2 = \left[N_{Lum} \times \left(\frac{Watt_{Lum} \times N_{hr}}{1{,}000} \times CR_{EN} \right) \right] \times Dur \tag{7.7}$$

$$LGC_3 = \left[N_{Lum} \times Cost_{Lum}^{OM} + Cost_{pole}^{OM} \right] \times Dur / 30 \tag{7.8}$$

$$LGC_4 = N_{Lum} \times Cost_{Lum}^{DM} + Cost_{pole}^{DM} \tag{7.9}$$

Where,

LGC_{area}, LGC_{fence}	= area unit cost of area lighting system and length unit cost of fence lighting system;
LGC_1, LGC_2, LGC_3, LGC_4	= installation, energy consumption, operation and maintenance, and demobilization costs of one light pole and N_{Lum} luminaires on its top;
S_{area}	= grid spacing in area lighting system;
S_{fence}	= spacing between light poles in fence lighting systems;
$Watt_{Lum}$	= energy consumption rate of one luminaire in watts;
N_{hr}	= number of lighting operation hours per day;
CR_{EN}	= cost rate of energy consumption ($/KWH);
Dur	= Project duration in days;

$Cost_{pole}^{inst}$, $Cost_{Lum}^{inst}$ = installation costs of light poles and luminaires;

$Cost_{pole}^{OM}$, $Cost_{Lum}^{OM}$ = operation and maintenance costs of light poles and luminaires; and

$Cost_{pole}^{DM}$, $Cost_{Lum}^{DM}$ = demobilization costs of light poles and luminaires.

7.4 Security-Cost Optimization

The main objective of this development phase is to formulate multi-objective optimization model for the problem of construction site security that is capable of generating optimal tradeoffs between minimizing security costs and minimizing security risks. This tradeoff exists because decreasing the level of security risk often demands additional expenditures to provide better security measures on site to counter potential threats. The formulation of the multi-objective optimization model is designed to consider and model the mutual impacts between site layout planning and security system performance. Accordingly, the decision variables in the present optimization model are categorized in two main groups: (1) security decision variables; and 2) layout decision variables. The following subsections describe in more details these two categories of decision variables and their impact on the considered objectives of minimizing security risks and cost.

7.4.1 Security Decision Variables

Security decision variables are design and implementation parameters of security countermeasures that directly impact the performance of the whole system. As shown in Figure 7.4, the security decision variables are distributed over the aforementioned three layers of the system: (1) site fence; (2) site grounds, and (3) target fence. First, the site fence security layer consists of the following decision variables: (1) location of site fence (*LC*) within the fixed boundaries (property lines) of the project; (2) fence type (FT_0); (3) intrusion detection system (IDS_0); and (4) fence lighting system (FL_0). Second, the design of site grounds layer requires making decisions on the selection of: (1) security response force (*RF*); and (2) area lighting system (*AL*). Third, the fence of each of the security targets (*R*) is similar to the site fence and it includes the following four decision variables: (1) security fence buffer (PB_r); (2) fence type (FT_r); (3) intrusion detection system (IDS_r); and (4) fence lighting system (FL_r). Table 7.1 lists examples of these security countermeasures and their attributes that impact the performance and cost of the security system.

Table 7.1 Attributes of Security Countermeasures

Security Countermeasure	Attribute	Description
Fence	DY_a	Average delay time (sec) for attacker *a*
	$Cost_{fence}^{inst}$	Installation unit cost (\$/m)
	$Cost_{fence}^{OM}$	Operation and Maintenance unit cost (\$/m/month)
	$Cost_{fence}^{DM}$	Demobilization unit cost (\$/m)
Lighting	LGP	Lighting performance (0 to 1) (Equation 1 and 2)
	LGC	Lighting unit cost (\$/m for fence lighting, \$/m^2 for area lighting) (Equation 4 – 9)
	S	Poles spacing (m)
Intrusion Detection System	DT_a	Probability of detection for attackers *a*
	$Cost_{IDS}^{inst}$	Installation unit cost (\$/m)
	$Cost_{IDS}^{OM}$	Operation and Maintenance unit cost (\$/m/month)
	$Cost_{IDS}^{DM}$	Demobilization unit cost (\$/m)
Response Force	$PD_{a,RF}$	Probability of detaining attacker *a*
	$Cost_{RF}$	Response force monthly cost (\$/month)
	I_{RF}	Onsite response index equals to 1 if the response force is patrolling inside the site, and 0 otherwise
	AT_{RF}	Action time (sec) using different probability distributions such as uniform, triangle, and normal distributions.

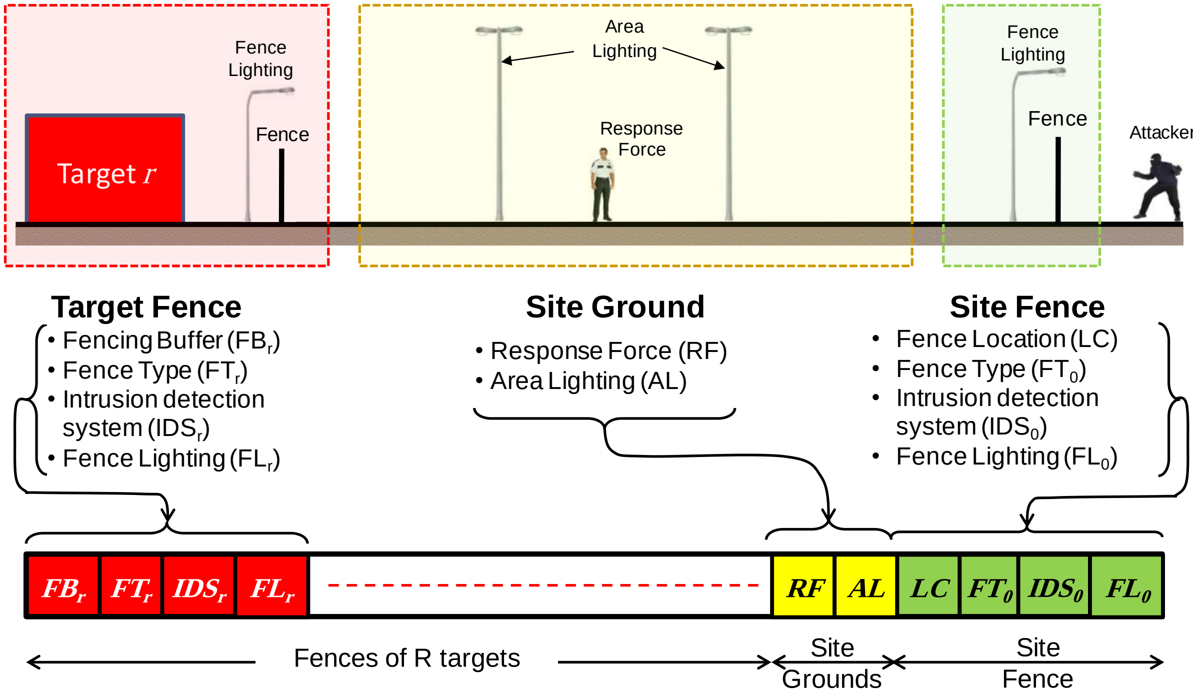


Figure 7.4 Decision Variables of Construction Site Security System

7.4.2 Layout Decision Variables

Dynamic site Layout planning requires making decisions on the positioning of moveable and stationary facilities considering imposed geometric constraints and security requirements. Layout decision variables represent the locations and orientations (0° or 90°) of each moveable facility and new stationary facilities in each construction stage (El-Rayes and Said 2009). Temporary facilities are positioned by defining the locations of their centroids at a set of grid locations that are defined based on a user-specified grid interval. Each stationary facility *i* needs only two decision variables (Loc_i and θ_i) to define its location and orientation that are fixed during its utilization time on site. On the other hand, positioning a moveable facilities *i* involves two decision variables ($Loc_{i,t}$ and $\theta_{i,t}$) for each stage of its existence onsite. For example, positioning the SCIF site office (stationary facility) in Figure 7.5 involves two decision variables (Loc_1 and θ_1), while positioning the storage area (moveable) involves four decision variables: $Loc_{2,1}$ and $\theta_{2,1}$ for the first stage and $Loc_{2,2}$ and $\theta_{2,2}$ for the second stage. The positioning of all temporary facilities should comply with four types of geometric constraints: (1) boundary; (2) overlap; (3) distance; and (4) zone constraints (El-Rayes and Said 2009). Furthermore, the model enables the consideration of additional constraints in order to prevent: (1) the positioning of temporary facilities within the fencing buffers of security targets; and (2) any overlap between temporary facilities and security lighting poles.

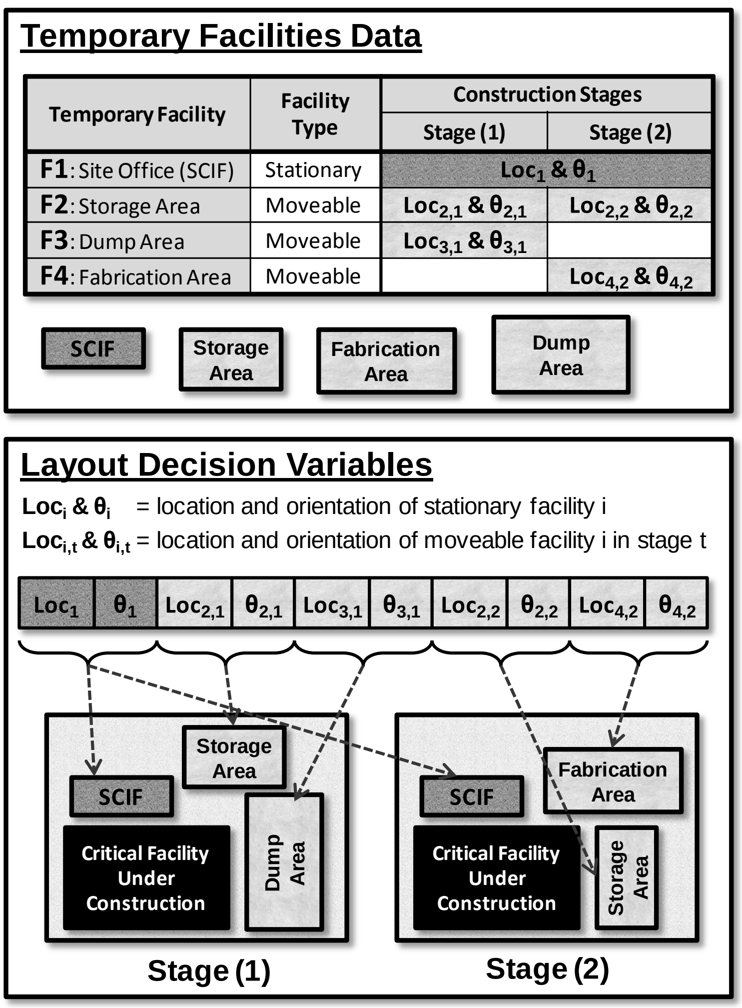


Figure 7.5 Decision Variables of Dynamic Site Layout Planning

7.4.3 Minimizing Security Risks

The first objective of the present framework is to minimize the overall security risk to potential targets on the construction site based on the attributes of the identified threats and the security system performance. As shown in Equation 7.10, the overall security risk (*OSRI*) is quantified in the present model as the ratio between (1) the reduction in the project risks due to the utilization of security countermeasures; and (2) the original project risks. Accordingly, the overall security risk (*OSRI*) is calculated based on three main variables: (1) the probability ($P_{a,r}^{t}$) of each attacker *a* posing a threat to target *r* in stage *t*; (2) the consequences ($C_{a,r}^{t}$) of a successful attack; and (3) the efficiency of the whole security system ($SE_{a,r}^{t}$) against such an attack, as shown in Equation 7.10. The probability ($P_{a,r}^{t}$) and consequence ($C_{a,r}^{t}$) of attacks are estimated in the first phase of the present framework (i.e. risk identification and system modeling phase). The security system effectiveness ($SE_{a,r}^{t}$) is calculated using Equation 7.11 which is designed to measure the performance of the system in terms of the main security functions of delaying, detecting, deterring, and detaining attacker *a* that is trying to breach target *r* in stage *t*. Accordingly, the security system effectiveness ($SE_{a,r}^{t}$) is calculated based on: (1) the probability of interruption ($PI_{a,r}$) that represents the delay and detection functions of the system; (2) the deterrence index ($DI_{a,r}^{t}$) that quantifies the deterrence of each security countermeasure against attacker *a* attempting to breach target *r*; and (3) the probability of detaining ($PD_{a,RF}$) attacker *a* by response force (*RF*). The probability of interruption ($PI_{a,r}$) and the deterrence index ($DI_{a,r}^{t}$) are described in more details in the following subsections, while the probability of detaining ($PD_{a,RF}$) is an attribute of each response force (*RF*) representing its probability of neutralizing attacker *a*, as shown in Table 7.1.

$$OSRI = \frac{\sum_{t=1}^{T}\sum_{a=1}^{A}\sum_{r=1}^{R} P_{a,r}^{t} \times C_{a,r}^{t} \times \left(1 - SE_{a,r}^{t}\right)}{\sum_{t=1}^{T}\sum_{a=1}^{A}\sum_{r=1}^{R} P_{a,r}^{t} \times C_{a,r}^{t}} \tag{7.10}$$

$$SE_{a,r}^{t} = PI_{a,r} \times PD_{a,RF} \times DI_{a,r}^{t} \tag{7.11}$$

Where,

$OSRI$ = overall security risk index;

A = number of attackers;

R = number of site security targets;

T = number of construction stages;

$P_{a,r}^{t}$ = probability that attacker *a* will attack target *r* in stage *t*;

$C_{a,r}^{t}$ = consequences of successful breach of attacker *a* toward target *r* in stage *t*;

$SE_{a,r}^{t}$ = effectiveness of security system against the threat of attacker *a* reaching target *r* in stage *t*;

$PI_{a,r}$ = probability of interrupting the intrusion of attacker *a* into target *r* in stage *t* that is calculated by the Intrusion Simulation Modules (*ISM*);

$PD_{a,RF}$ = probability of detaining attacker *a* by applied response force (*RF*); and

$DI_{a,r}^{t}$ = overall deterrence index (0 to 1) to represent the effect of security measures on attacker *a* tendency to breach target *r* in stage *t* where higher value represent high deterrence of the security system.

The probability of interruption is the probability that selected response force will interrupt attackers before achieving their goals based on the performance of the delay and detection countermeasures and the construction site layout. As shown in Figure 7.6, the probability of interruption ($PI_{a,r}$) depends on two main parameters (Hicks et al 1998): (1) the delay time ($IDAD_{a,r}$) of intruder *a* after detecting his/her attempt to breach target *r*; and (2) the commutative distribution function of the action time of response force *RF* (AT_{RF}) that is defined as an attribute for each response force (see Table 7.1). A newly developed intrusion simulation module (*ISM*) is utilized to estimate the intruder delay time after detection ($IDAD_{a,r}$) that represents the time from the attacker's detection to the time of completing the attack. The intruder delay time after detection ($IDAD_{a,r}$) in this module is estimated based on: (1) fences delay times for attacker *a*; (2) detection probabilities of intrusion detection systems for attacker *r*; and (3) site layout that specifies the locations of security fences as well as potential target *r*. This intruder delay time ($IDAD_{a,r}$) is then used in combination with the action time (AT_{RF}) distribution function to estimate the probability ($PI_{a,r}$) of interrupting the intrusion of attacker *a* into target *r*, as shown in Figure 7.6. The computations of the developed intrusion simulation module are performed using the following five main steps:

I. **Calculate site fence delay**: The simulation module first checks if the attacker is detected by the IDS of the site fence based on the IDS detection probability ($DT_a^{IDS_0}$). If the attacker is detected, the detection time (*T1*) is recorded and the clock variable (*CLOCK*) is incremented to account for the delay time required by the intruder to overcome the site fence ($DY_a^{FT_0}$).

II. **Calculate site grounds delay**: The *CLOCK* variable is incremented to account for the time that the attacker needs to get to the fence of the target based on the specified probability distribution of potential attacker's speed (v_a) and the shortest distance between the site fence and target fence (L_r) that is identified based on the site layout plan.

III. **Calculate target fence delay**: If the attacker is not detected in the site fence, the simulation module checks if the detection occurs in the target fence similar to step (*I*) considering the detection probability of the target fence IDS ($DT_a^{IDS_r}$). If the attacker is detected, the detection time is recorded as (*T1*) and the *CLOCK* variable is incremented to account for the target fence delay time ($DY_a^{FT_r}$).

IV. **Calculate target buffer delay:** The *CLOCK* variable is incremented to include the time that the attacker needs to get to the target considering the specified probability distribution of attacker's speed (v_a) and the target's fencing buffer (FB_r).

V. **Calculate escape duration, if needed:** Steps *I* through *IV* are repeated if the motive of the attacker is to steal classified information and escape (*TwoWay* = *True*), otherwise simulation run is terminated if the motive of the attacker is to destroy valuable assets onsite (*TwoWay* = *False*). At the end of the simulation run, the attack completion time (*T2*) is recorded as the latest *CLOCK* time that considered all the delays encountered by the intruder. As shown in Figure 7.6, the detection time (*T1*) is subtracted from the attack completion time (*T2*) in order to calculate the intruder delay time after detection ($IDAD_{a,r}$). Steps *I* through *V* are then repeated for *N* simulation runs to estimate the average value of the intruder delay time after detection ($IDAD_{a,r}$).

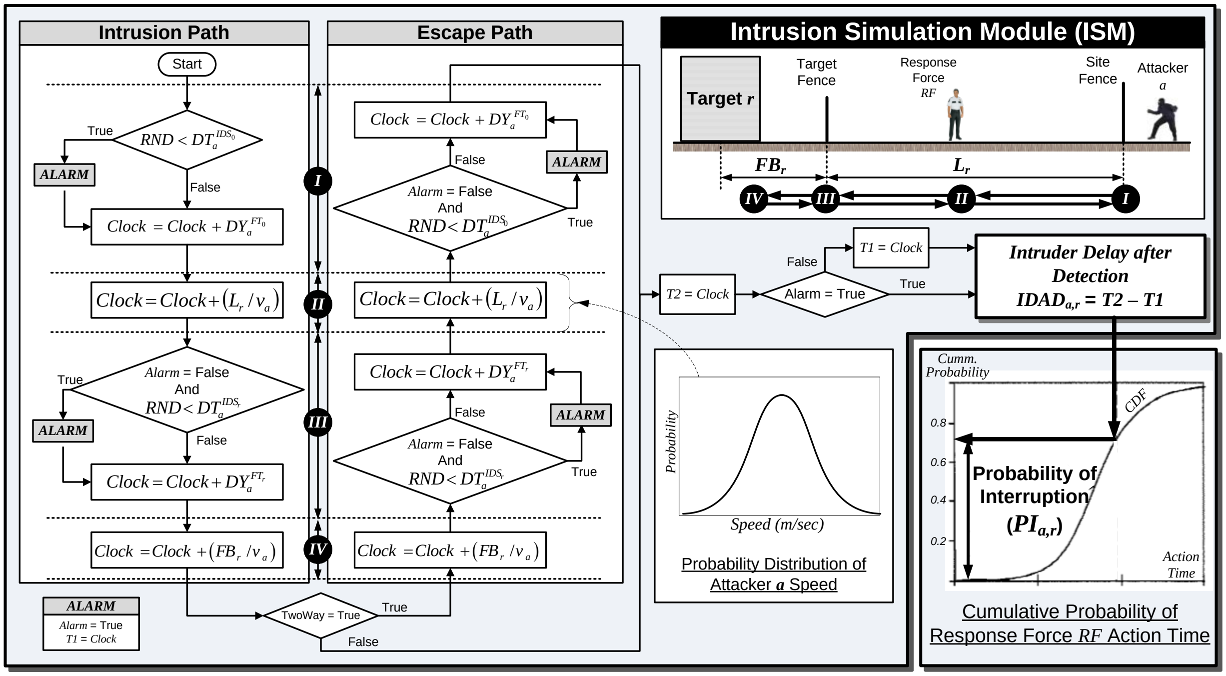


Figure 7.6 Quantification of Interruption Probabilities using Intrusion Simulation Module

The second factor that significantly controls security system effectiveness is the deterrence index ($DI^{t}_{a,r}$) that is used to quantify the impact of applied security measures on reducing attackers tendency for intrusion. As shown in Equation 7.12, deterrence index ($DI^{t}_{a,r}$) is a newly developed metric that integrates the deterrence effect of: (1) lighting systems (DI^{LG}_{r}); (2) response forces (DI^{RF}_{r}); (3) fences ($DI^{FN}_{a,r}$); (4) intrusion detection systems ($DI^{IDS}_{a,r}$); and (5) natural surveillance ($DI^{NS}_{r,t}$). As shown in Equation 7.12, the collective impact of these deterrence factors on each attacker *a* is aggregated and quantified using a set of weighting factors (w^{LG}_{a} , w^{NS}_{a} , w^{RF}_{a} , w^{FN}_{a} , w^{IDS}_{a}) that are defined in the phase of risk identification and system modeling. The computation of this overall deterrence index is based on the reported literature which found deterrence to be dependent mainly on the physical appearance of individual countermeasures (Cozens et al. 2005; Vellani 2007). First, the deterrence of the lighting systems (DI_r^{LG}) is calculated using Equation 7.13 as the average performance of lighting systems that are utilized in site fence, site area, and fence of target *r*. Second, the deterrence of response forces (DI_a^{RF}) occurs only if onsite forces are utilized (i.e. I_{RF} = 1) and is quantified using Equation 7.14 as the ratio between the detaining probability (DN_a^{RF}) of attacker *a* by response force (*RF*) and the max detaining probability ($DN_a^{\max}$) that can be achieved by the best available response force. Third, the deterrence of fences for attacker attempting to breach target *r* ($DI_{a,r}^{FN}$) is calculated by Equation 7.15 as the ratio between the delay times ($DY_a^{FT_0}$ and $DY_a^{FT_r}$) of the fences used for the fence of the site and target *r* and the maximum delay time ($DY_a^{\max}$) that can be achieved by the best available fence. Fourth, the deterrence of IDS is similarly calculated using Equation 7.16 as the ratio between detection probabilities of the IDS used in the fence of the site and target *r* ($DT_a^{IDS_0}$ and $DT_a^{IDS_r}$) and the detection probability ($DT_a^{\max}$) of the best available IDS.

The fifth and final factor that contributes to the deterrence of construction site security is natural surveillance and clear field of sight around security targets. The deterrence impact ($DI_{r,t}^{NS}$) of target *r* natural surveillance is calculated using Equation 7.17 as the ratio between the area of existing isovist (visibility) field (Davis and Benedikt 1979; Soltani and Fernando 2004) of target *r* considering the layout of site facilities ($IsoA_{r,t}$) and the maximum isovist field that can be achieved without the existence of these facilities ($IsoA_{r,t}^{\max}$). As shown in Figure 7.7, the isovist field is represented as a polar array of isovist lines emerging from the center of target *r* and intersecting with either the closest site facility or site fence. The array of isovist lines is generated with an arbitrary number of lines (N_{iso}) specified by the user, where small N_{iso} results in high precision isovist zones but inquire high computational overhead. Accordingly, the area of isovist field is calculated as the length summation of all isovist lines. It should be noted that site layout plan is the main controlling factor of natural surveillance as isovist field around targets can be increased by either: (1) positioning site facilities as far as possible from the target such as positioning facility TF1 away from target facility in Figure 7.7; or (2) aligning temporary facilities in a way to minimizing the surveillance obstruction such as positioning TF5 behind TF4 that does not result in additional reduction of the isovist field. It should be noted that the security system components are assumed to be static with fixed countermeasures over the entire project duration because any system alterations might result in adverse effects related to system performance and cost. However, the security system performance is dynamic and varies based on the changes in the deterrence of the site security system and the natural surveillance.

$$DI_{a,r}^{t} = w_a^{LG} \times DI_r^{LG} + w_a^{RF} \times DI_a^{RF} + w_a^{FN} \times DI_{a,r}^{FN} + w_a^{IDS} \times DI_{a,r}^{IDS} + w_a^{NS} \times DI_{r,t}^{NS} \tag{7.12}$$

$$DI_r^{LG} = \left(LP_{FL_0} + LP_{AL} + LP_{FL_r}\right)/3 \tag{7.13}$$

$$DI_a^{RF} = \left(\frac{DN_a^{RF}}{DN_a^{\max}}\right) \times I_{RF} \tag{7.14}$$

$$DI_{a,r}^{FN} = \frac{DY_a^{FT_0} + DY_a^{FT_r}}{2 \times DY_a^{\max}} \tag{7.15}$$

$$DI_{a,r}^{IDS} = \frac{DT_a^{IDS_0} + DT_a^{IDS_r}}{2 \times DT_a^{\max}} \tag{7.16}$$

$$DI_{r,t}^{NS} = \frac{IsoA_{r,t}}{IsoA_{r,t}^{\max}} \tag{7.17}$$

Where,

w_a^{LG}, w_a^{NS}, w_a^{RF}, w_a^{FN}, w_a^{IDS} = weighting factors of attacker *a* for the deterrence of security countermeasures of lighting, natural surveillance, response force, fences, and intrusion detection systems, respectively;

DI_r^{LG}, DI_a^{RF}, $DI_{a,r}^{FN}$, $DI_{a,r}^{IDS}$, $DI_{r,t}^{NS}$ = deterrence indices (0 to 1) to represent the effect of different security measures (lighting, response force, fences, intrusion detection systems, and natural surveillance respectively) on attacker *a* tendency to breach for target *r*;

LP_{FL0}, LP_{AL}, LP_{FLr} = lighting performance for selected lighting systems of site fence (FL_0), site grounds (AL), and target *r* (FL_r), respectively;

DN_a^{RF}, $DN_a^{\max}$ = detain probability of selected response force *RF* interrupting attacker *a* and maximum detain probability of attacker *a* for all considered response forces;

I_{RF} = onsite response index equals to 1 if the response force is patrolling inside the site, and 0 otherwise;

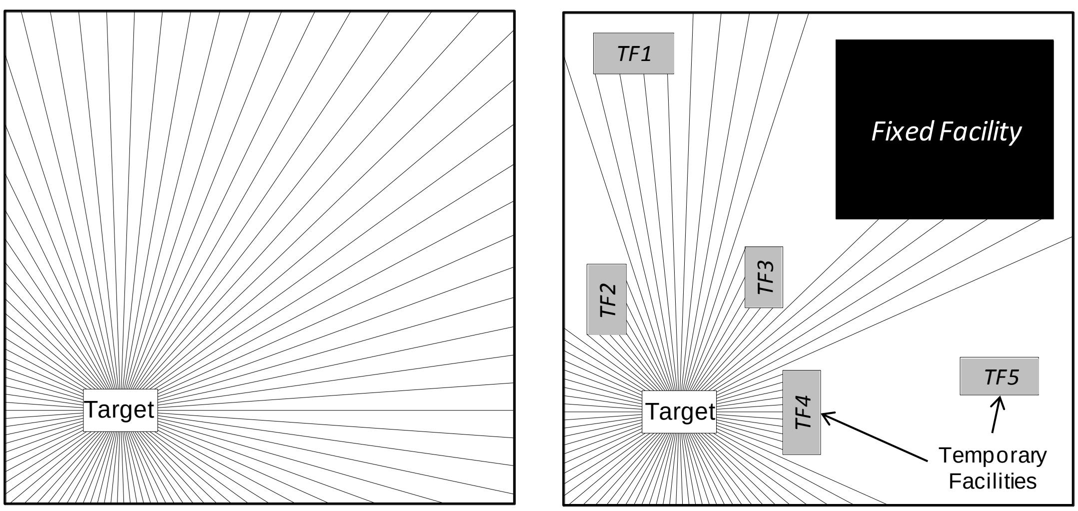
$DY_a^{FT_0}$, $DY_a^{FT_r}$ = delay times of attacker a by fences selected for site and target r fences;

$DY_a^{\max}$ = maximum delay times of attacker a for all considered options of fences;

$DT_a^{IDS_0}$, $DT_a^{IDS_r}$ = detection probabilities of attacker a by IDS selected for site and target r fences;

$DT_a^{\max}$ = maximum detection probability of attacker a for all considered options of IDS; and

$IsoA_{r,t}$, $IsoA_{r,t}^{\max}$ = actual and maximum values for the area of isovist zones around temporary facility classified as target r in stage t;



$$IsoA_r^{\max} = \sum_i^{N_{iso}} IsoL_i^{\max}$$

$$IsoA_r = \sum_i^{N_{iso}} IsoL_i$$

Figure 7.7 Quantification of Natural Surveillance using Isovist Fields

7.4.4 Minimizing Overall Site Cost

The second objective of the present framework is to minimize the overall site cost that includes security system costs and layout costs, as shown in Equation 7.18. First, the security system cost (*SSC*) is broken down as shown in Equations 5.19 through 5.22 to cover all the costs (i.e. installation, operation and maintenance, and demobilization costs) of security countermeasures that are used in the following three main layers of the security system: (1) site fence layer (SSC_{SP}); (2) site grounds layer (SSC_{SG}); and (3) target r layer (SSC_r). It should be noted that the lighting cost of the site fence (LGC_{FT_0}), site grounds (LGC_{AL}), and target fence (LGC_{FT_r}) are already generated from the lighting optimization phase that considered all of the lighting lifecycle costs. Second, the site layout cost (*LYC*) consists of two main components, as shown in Equation 7.26 (El-Rayes and Said 2009): (1) resource travel costs (RTC) that represent the travel cost of labor and equipment between fixed, moveable, and stationary facilities over the duration of project, as shown in Equation 7.27; and (2) facilities relocation costs (FRC) that represent the cost of relocating moveable facilities in every construction stage, as shown in Equation 7.28.

$$OSC = SSC + LYC \tag{7.18}$$

$$SSC = SSC_{SP} + SSC_{SG} + \sum_{r=1}^{R} SSC_r \tag{7.19}$$

$$SSC_{SP} = SP_{PL} \times \left[Cost_{SP}^{inst} + Cost_{SP}^{OM} \times \left(\frac{Dur}{30} \right) + Cost_{SP}^{DM} \right] \tag{7.20}$$

$$SSC_{SG} = SA_{PL} \times LGC_{AL} + Cost_{RF} \times Dur / 30 \tag{7.21}$$

$$SSC_r = SP_{PB_r} \times \left[Cost_r^{inst} + Cost_r^{OM} \times \left(\frac{Dur}{30} \right) + Cost_r^{DM} \right] \tag{7.22}$$

$$Cost_B^{inst} = \left(Cost_{FT_B}^{inst} + Cost_{IDS_B}^{inst} + LGC_{FT_B} \right) \tag{7.23}$$

$$Cost_B^{OM} = \left(Cost_{FT_B}^{OM} + Cost_{IDS_B}^{OM} \right) \tag{7.24}$$

$$Cost_B^{DM} = \left(Cost_{FT_B}^{DM} + Cost_{IDS_B}^{DM} \right) \tag{7.25}$$

$$LYC = RTC + FRC \tag{7.26}$$

$$RTC = \sum_{t=1}^{T} \sum_{i=1}^{NF_t - 1} \sum_{j=i+1}^{NF_t} C_{ij}^t \times D_{ij}^t \tag{7.27}$$

$$FRC = \sum_{t=1}^{T} \sum_{i=1}^{NF_t^M} E_i \times RC_i \times IF \left\{ D_i^{t,t-1} > 0 \quad OR \quad \theta_{i,t} \neq \theta_{i,t-1} \right\} \tag{7.28}$$

Where,

SSC = security system cost;

LYC = site layout cost;

SSC_{SP}, SSC_{SG}, SSC_r = cost of security countermeasures applied in site fence, site grounds, and target *r* fence, respectively;

SP_{LC} = security fence length of construction site considering option LC of fence locations (m);

SA_{LC} = construction site area using option *PL* of fence locations (m);

SP_{PB_r} = security fence length of target *r* considering the chosen fencing buffer (FB_r);

LGC_{FT_0}, LGC_{AL}, LGC_{FT_r} = cost rate of lighting systems applied in site fence, site grounds, and target *r* fence, respectively;

$Cost_B^{inst}$, $Cost_B^{OM}$, $Cost_B^{DM}$ = installation, operation and maintenance, and demobilization costs of security countermeasures on barrier *B*, which is either around target *r* or the whole site *SP*.

RTC = resource travel cost;

FRC = facilities relocation cost;

NF_t = number of site facilities (i.e. fixed, stationary, and moveable) in stage t;

NF_t^M = number of moveable facilities in stage t;

$C_{i,j}^t$, $D_{i,j}^t$ = travel cost rate and distance between facilities i and j in stage t;

E_i = facilities existence factor equals to 1 if the moveable facility *i* exists in previous stage *t-1*, and 0 otherwise;

RC_i = relocation cost of moveable facility *i*;

IF{condition} = a conditional function that returns 1 if the inside condition is satisfied, 0 otherwise;

$D_i^{t,t-1}$ = Euclidian distance between facility *i* positions in stages *t* and *t*-1; and

$\theta_{i,t}$ = orientation angle of facility *i* in stage *t*;

7.5 Performance Evaluation

The main purpose of this phase is to evaluate the performance of the present framework in optimizing construction site security of critical infrastructure. The framework is evaluated using an application example that represents the construction of a critical infrastructure facility over three stages with a total duration of 465 days. In this example, the risk identification and system modeling phase of the present framework generated the following site layout and security data: (1) dynamically changing space needs for construction site facilities that are listed in Table 7.2, the travel cost rates between site facilities as shown in Table 7.3, and available options of site fence as shown in Figure 7.8; (2) security targets, which include the critical facility under construction (F1) and the site administration area (F2) that includes sensitive compartmented information (SCI); (3) potential attackers that include a criminal threat (a_1) and a hostile group (a_2); (4) security threats that can dynamically change over the project stages Table 7.4; (5) available options for security countermeasures and equipments as shown in Tables 5.5 and 5.6; (6) cumulative probability distribution of action times of response forces as shown in Figure 7.9; (7) probability distribution of potential attackers' speed as shown in Figure 7.9; (8) detection probabilities for each pair of IDS option and attacker as shown in Table 7.7; (9) delay times for each pair of attacker and fence option as shown in Table 7.7; (10) detaining probabilities for each pair of attacker and response force option as shown in Table 7.7; (11) lighting requirements that recommends an average horizontal illuminance level between 5 and 15 lux with a maximum uniformity ratio of 8; (12) deterrence weighting factors that are assumed to have the same weight for all attackers (i.e. $w_a^{LG} = w_a^{NS} = w_a^{RF} = w_a^{FN} = w_a^{IDS} = 0.2$); and (13) other analysis parameters related to lighting and security-cost optimization, as shown in Table 7.8.

Table 7.2 Site Facilities Dimensions and Utilization Onsite

Facilities with fixed positions

ID	Description	dimensions		Time on site			Fixed position*	
		Lx	Ly	T1	T2	T3	x	y
F1	Critical Facility under Construction	90	60	√	√	√	95	120

Temporary Facility

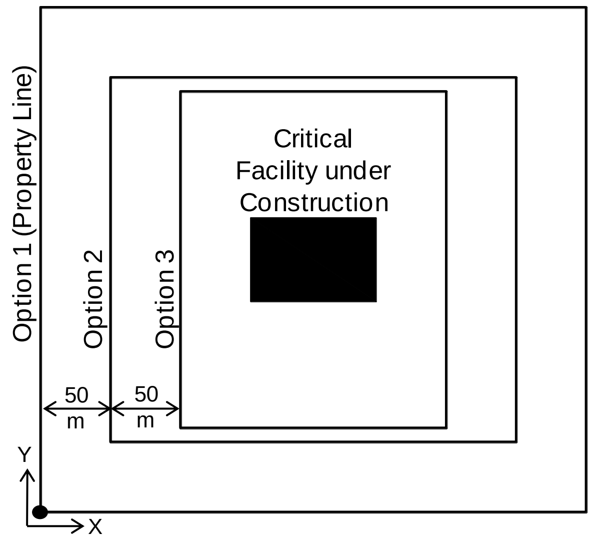
ID	Description	dimensions		Time on site			Type**	Relocation Cost
		Lx	Ly	T1	T2	T3		
F2	Site Administration Area	30	30	√	√	√	S	N.A.
F3	Dump Area (1)	40	20	√	√	√	M	7,500
F4	Dump Area (2)	30	15	√	-	-	M	7,500
F5	Lay-down Area (1)	25	25	√	√	√	M	6,000
F6	Lay-down Area (2)	25	15	-	√	√	M	6,000
F7	Fabrication Area	35	20	√	√	√	M	3,000
F8	Labor Rest Area	20	20	√	√	√	M	1,500

** Coordinates are measured from the bottom left corner of the boundary/property line of the site (See Figure 7.8)*

*** S = Stationary   M = Moveable*

Table 7.3 Travel Cost Rates ($/m) between Site Facilities

Facility (i)	**Facility (j)**							
	F1	**F2**	**F3**	**F4**	**F5**	**F6**	**F7**	**F8**
F1	0	60	50	40	100	80	50	10
F2	-	0	2	2	20	20	20	2
F3	-	-	0	0.0	0.0	0	0	0
F4	-	-	-	0	0.0	0	0	0
F5	-	-	-	-	0	5	20	5
F6	-	-	-	-	-	0	15	5
F7	-	-	-	-	-	-	0	5
F8	-	-	-	-	-	-	-	0



Option (PL)	Lx (m)	Ly (m)	SP_{PL} (m)	SA_{PL} (m^2)
1	390	360	1,500	140,400
2	290	260	1,100	75,400
3	190	240	860	45,600

Figure 7.8 Available Options for Site Fence

Table 7.4 Potential Security Threats

ID	Target (r)	Attacker (a)	Stage (t)	Probability ($P^t_{a,r}$)	Consequences ($C^t_{a,r}$)	Type
1	1	1	1	0.1	0.2	Two-way (steal SCI or investigate critical facility under construction)
2	1	1	2	0.5	0.9	
3	1	1	3	0.9	0.9	
4	1	2	1	0.1	0.5	
5	1	2	2	0.2	0.5	
6	1	2	3	0.7	0.5	
7	1	1	1	0.1	0.1	
8	1	1	2	0.2	0.2	
9	1	1	3	0.3	0.5	
10	1	2	1	0.3	0.5	
11	1	2	2	0.5	0.7	
12	1	2	3	0.7	0.9	

Table 7.5 Options for Fences, Intrusion Detection Systems, and Response Forces

No.	Name	Installation Cost $Cost_{fence}^{inst}$ ($/m)	O&M Cost $Cost_{fence}^{OM}$ ($/m/month)	Demobilization Cost $Cost_{fence}^{DM}$ ($/m)
Fences				
1	Barbed Wire	25	5	- 0.1
2	Barbed Tape	30	5	0
3	Chain Link	90	20	0
4	Electric Fencing	150	40	- 2

Intrusion Detection Systems

No.	Name	Installation Cost $Cost_{IDS}^{inst}$ ($/m)	O&M Cost $Cost_{IDS}^{OM}$ ($/m/month)	Demobilization Cost $Cost_{IDS}^{DM}$ ($/m)
1	Taut-Wire Sensor	50	1	- 10
2	Fiber-Optic Cable	120	5	- 30
3	Electric-Field Sensor	175	15	- 50
4	Capacitance Proximity Sensor	225	30	- 100

Response Forces

No.	Description	Onsite	Monthly Cost ($/month)
1	Offsite Local Forces	No	1,000
2	Site Patrol (3 guards)	Yes	10,000
3	Site Patrol (4 guards + 2 dogs)	Yes	20,000

Table 7.6 Options for Lighting Poles and Luminaires

Light Poles					
No.	Height (m)		Installation Cost $Cost_{pole}^{inst}$ ($)	O&M Cost $Cost_{pole}^{OM}$ ($/month)	Demobilization Cost $Cost_{pole}^{DM}$ ($)
1	3		300	0	- 50
2	5		450	0	- 200
3	6		750	0	- 500
4	7.5		900	0	- 650
5	9		1000	0	- 750
Luminaires*					
No.	Energy (watt)	Shape	Installation Cost $Cost_{Lum}^{inst}$ ($)	O&M Cost $Cost_{Lum}^{OM}$ ($/month)	Demobilization Cost $Cost_{Lum}^{DM}$ ($)
1	100	Circular	150	5	- 100
2	150	Circular	200	5	- 100
3	200	Circular	375	5	- 100
4	320	Circular	450	5	- 100
5	400	Circular	550	5	- 100
6	1000	Circular	750	5	- 100
7	100	Rectangular	150	5	- 100
8	125	Rectangular	150	5	- 100
9	175	Rectangular	250	5	- 100
10	250	Rectangular	400	5	- 100
11	400	Rectangular	550	5	- 100
12	1000	Rectangular	800	5	- 100
13	250	Square	400	5	- 100
14	400	Square	550	5	- 100
15	750	Square	650	5	- 100
16	1000	Square	800	5	- 100

* The number of possible luminaires for each pole is a decision variable that can take a value of 1, 2, or 4.

Table 7.7 Attackers Delay Times, Detection and Detain Probabilities

Attacker (a)	Delay Times		Detection Probabilities		Detaining Probabilities	
	Fence (FT)	DY_a^{FT} (sec)	IDS	DT_a^{IDS} (%)	Response Force (RF)	DN_a^{RF} (%)
1	1	20	1	60	1	70
	2	45	2	75	2	80
	3	60	3	85	3	95
	4	90	4	95		
2	1	10	1	40	1	60
	2	30	2	60	2	75
	3	45	3	70	3	90
	4	60	4	80		

Table 7.8 Analysis Parameters

Analysis Parameter	**Value**
Range of fencing buffer around target 1 (FB_1) (m)	10 – 40
Range of fencing buffer around target 2 (FB_2) (m)	5 – 30
Range of spacing between light poles (m)	6 – 50
Pitch of site location grid (m)	1
Pitch of lighting calculation grid (m)	0.5
Fence lighting width (FLW) (m)	10
Number of simulation runs (N)	100
Cost rate of energy consumption (CR_{EN}) ($/KWH)	0.2
Number of isovist lines (N_{iso})	90

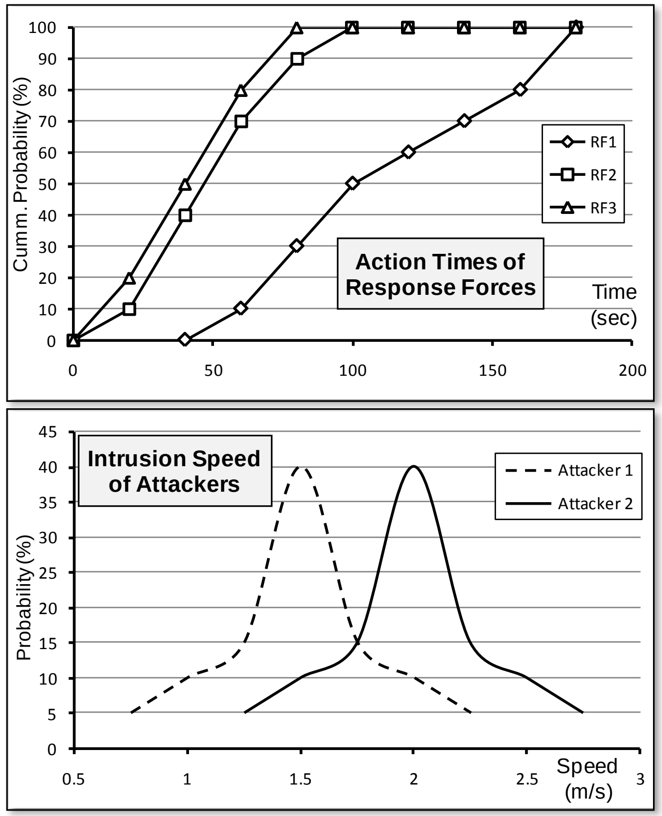
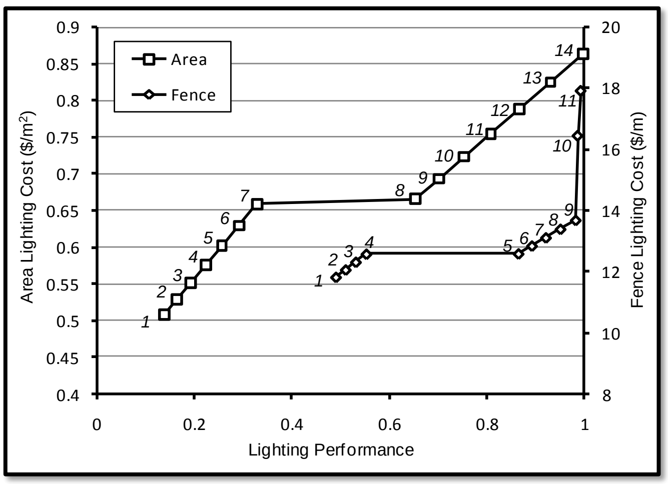


Figure 7.9 Action Times of Response Forces and Intrusion Speed of Attackers

The area and fence lighting systems in this example are optimized in order to generate optimal tradeoffs between maximizing the lighting performance and minimizing cost. The results of this security lighting optimization phase (see Figure 7.10) clearly illustrates the tradeoff between lighting performance and cost as improving performance requires additional cost by either decreasing the spacing between light poles or selecting brighter luminaires. As shown in Figure 7.10, all generated solutions consider only one luminaire per pole with low energy consumption (100 to 400 watts) to fulfill the specified illuminance and uniformity requirements. The lighting optimization results in Figure 7.10 also emphasize the effect of poles spacing on lighting performance compared to the impact of luminaire type. For example, solutions 1 through 7 of the area lighting provide gradual improvements in lighting performance by using the same luminaire (luminaire 13 in Table 7.6) and reducing the spacing. On the other hand, solution 8 has a significant improvement compared to solution 7 because of the use of a better luminaire with higher energy (luminaire 14 in Table 7.6). These optimal solutions are considered as possible options of fence and area lighting systems in the next phase of security-cost optimization as they provide a wide range of tradeoffs between lighting cost and performance.



Area Lighting				
ID	*Lum*	N_{Lum}	*H*	*S*
1	13			49
2	13			48
3	13			47
4	13			46
5	13			45
6	13			44
7	13	1	9	43
8	14			49
9	14			48
10	14			47
11	14			46
12	14			45
13	14			44
14	14			43

Fence Lighting				
ID	*Lum*	N_{Lum}	*H*	*S*
1	7			50
2	7			49
3	7			48
4	7			47
5	8			50
6	8	1	3	49
7	8			48
8	8			47
9	8			46
10	9			49
11	7			33

Lum = Luminaire type
N_{Lum} = Number of luminaires
H = Pole height
S = Poles spacing

Figure 7.10 Optimal Tradeoff Solutions of Fence and Area Lighting Systems

The present framework was utilized to optimize construction site security for this example in order to optimize the conflicting objectives of minimizing overall security risks and minimizing overall site cost. As shown in Table 7.9, the security-cost optimization in this example requires specifying the values of 38 decision variables that include: (1) 25 dynamic layout decision variables; and (2) 13 security decision variables. Considering the possible options for each decision variable, there are 3.14×10^{17} possible combinations for the plan of site security system and layout within only the first option of site fence. The present framework implements a multi-objective genetic algorithm (Deb et al 2000) to search this large space of possible solutions for the optimal plan of site security system and layout. As shown in Figure 7.11, the present framework generated a wide spectrum of optimal tradeoff solutions that range from: (1) minimum security layout (solution A) that results in the maximum overall cost; and (2) minimum cost layout (Solution B) that creates the highest overall security risks. Construction Planners can select and focus on one or more solutions from this set of optimal tradeoff solutions, which satisfies their acceptable level of security risks while complying with available budgets. To illustrate the capabilities of the developed framework, the two extreme solutions are analyzed in more details in the following subsections.

Table 7.9 Number of Decision Variables and Possible Combinations

Decision Variable		Number	Possible options	Notes	Number of combinations
Layout	Locations of temporary facilities over stages	16	139,651* 74,851** 45,171***	Table 7.2 and Figure 7.8	3.14×10^{17}* 1.7×10^{17}** 1×10^{17}***
	Orientations of rectangular temporary facilities over stages	9	2		
Security	Target 1 fencing buffer (*FB_1*)	1	30	Table 7.8	
	Target 2 fencing buffer (*FB_2*)	1	25	Table 7.8	
	Targets fence type (*FT_r*)	2	4	Table 7.5	
	Targets IDS (*IDS_r*)	2	4	Table 7.5	
	Targets fence lighting (*FL_r*)	2	11	Figure 7.10	
	Response force (*RF*)	1	3	Table 7.5	
	Site Area lighting (*AL*)	1	14	Figure 7.10	
	Site fence type (*FT_0*)	1	4	Table 7.5	
	Site IDS (*IDS_0*)	1	4	Table 7.5	
	Site fence lighting (*FL_0*)	1	11	Figure 7.10	

* First option of site fence
** Second option of site fence
*** Third option of site fence

As shown in Figure 7.12 and Table 7.10, solution A was able to provide the minimum overall security risks for this example by: (1) generating an optimal combination of security decision variables that effectively accomplish the four functions of the system (i.e. deter, detect, delay, and detain); and (2) providing a high level of natural surveillance around targets that contributes to the deterrence of the security system. As shown in Table 7.10, the best security countermeasures in terms of performance are selected for almost all security decision variables in addition to the selection of the first option of site fence to increase the intrusion distance for attackers. Furthermore, temporary facilities are positioned in a way that maximizes the natural surveillance around targets by either positioning temporary facilities away as much as possible from targets or using already existing blind areas to position facilities. As shown in Figure 7.12, temporary facilities are relocated between the construction stages to dynamically improve the site's natural surveillance against increasing security threats (see Table 7.4).

On the other hand, solution B was the optimal in minimizing overall site cost, as shown in Figure 7.12 and Table 7.10, by: (1) utilizing the least expensive security countermeasures in all security system layers that satisfy the minimum security requirements; and (2) minimizing resource travel costs by positioning temporary facilities close to each other. Analyzing the optimization results for this example also demonstrate that: (1) the site layout was dynamically changed in each stage to improve natural surveillance around targets because of increased security risks over the construction duration for both solutions A and B; (2) zero-security risks solution cannot be achieved because of the unavailability of perfect options of some critical countermeasures such as response force with 100% detaining probability; and (3) the third alternative of site fence was not considered largely in optimal tradeoff solutions compared to the other two options (see Figure 7.11) as available options of fences provided sufficient delay times for attackers.

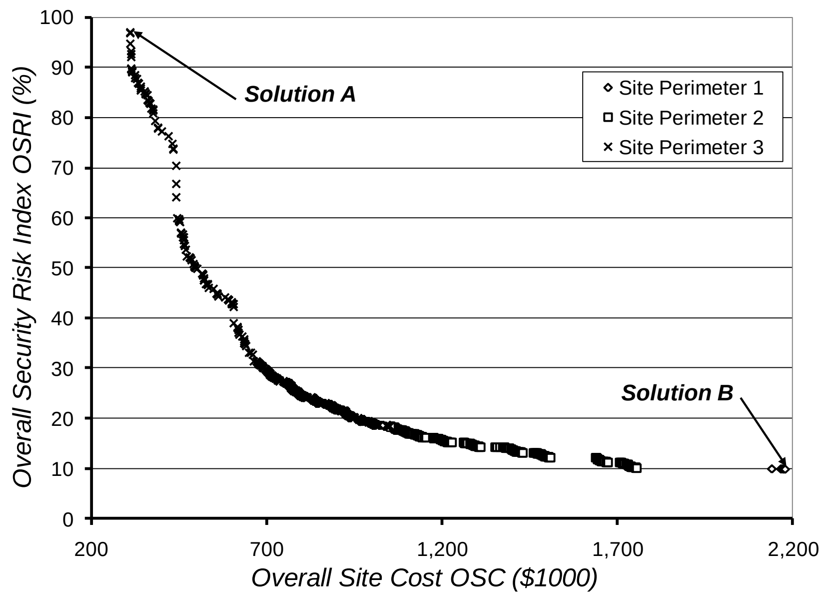


Figure 7.11 Generated Optimal Tradeoff Solutions

Table 7.10 Generated Optimal Values of Security Decision Variables

Layer	Security Decision Variable	Solution A	Solution B
Site fence	Fence Location (*FL*)	option 1	option 3
	Fence Type (FT_0)	option 4	option 1
	Intrusion Detection (IDS_0)	option 2	option 1
	Fence Lighting (FL_0)	option 9	option 1
Site Grounds	Response Force	option 3	option 1
	Area Lighting	option 12	option 1
Target (1) fence	Fencing Buffer (FB_1)	10 m	10 m
	Fence Type (FT_1)	option 4	option 1
	Intrusion Detection (IDS_1)	option 2	option 1
	Fence Lighting (FL_1)	option 9	option 2
Target (2) fence	Fencing Buffer (FB_2)	5 m	5 m
	Fence Type (FT_2)	option 4	option 1
	Intrusion Detection (IDS_2)	option 3	option 1
	Fence Lighting (FL_2)	option 9	option 1

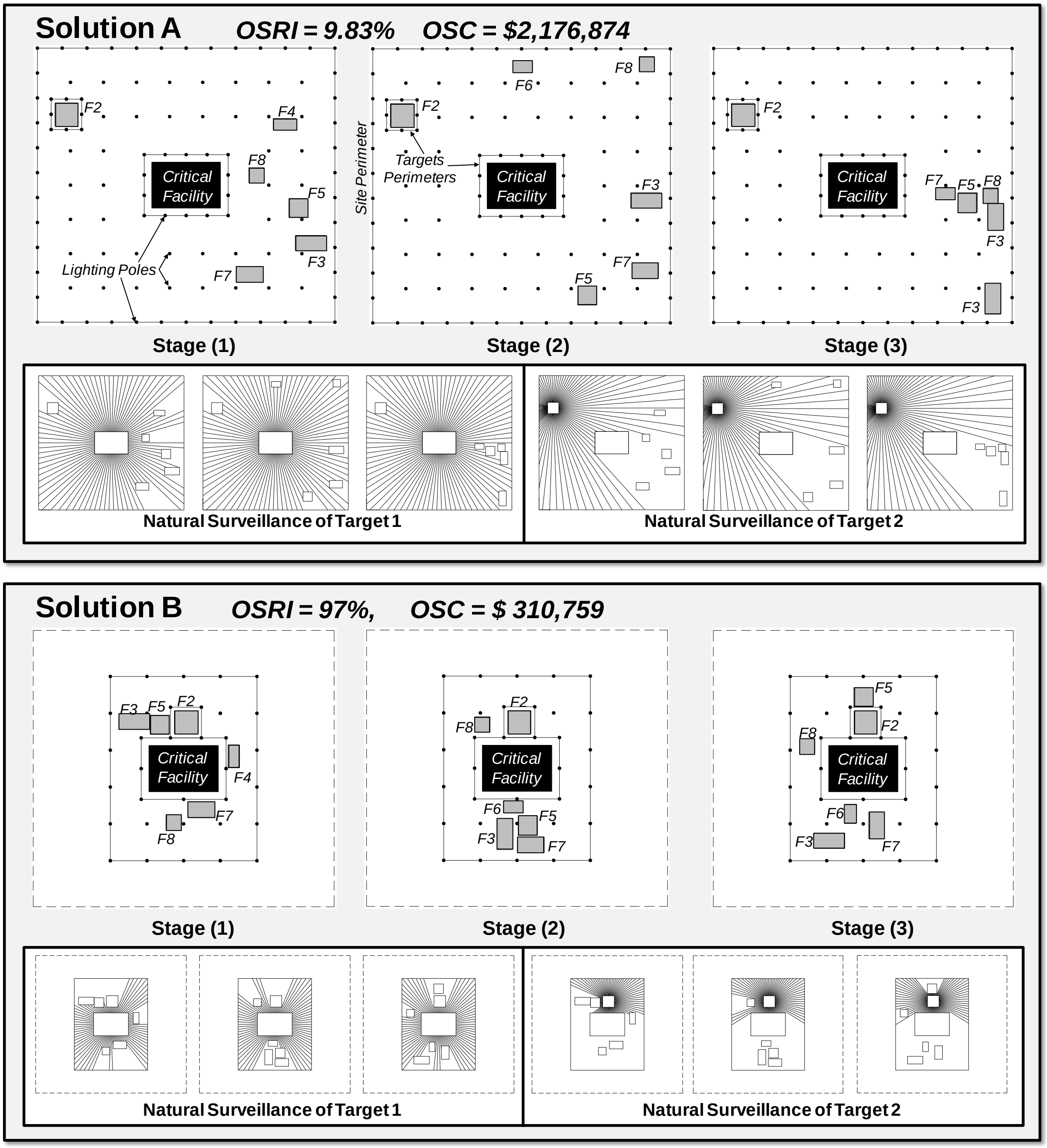


Figure 7.12 Site Layout Plans of Optimal Tradeoff Solutions A and B

7.6 Summary

This chapter presented the development of a multi-objective framework to enable construction managers and security officers to plan and optimize the utilization of physical security systems on the construction sites of critical infrastructure projects. The framework is devised to simultaneously minimize overall security risks and minimize overall site costs. To enable the quantification and minimization of overall security risks during the construction stage, the automated framework incorporates the development of: (1) a multi-objective optimization model for optimizing area and fence lighting systems in order to minimize lighting costs and maximize lighting performance; (2) an intrusion simulation model to estimate the delay time of attackers after detection given the performance of the utilized security countermeasures onsite; and (3) a new metric of quantifying the deterrence of the system and the impact of security countermeasures to deter potential threats. The overall site costs in the present framework include the costs of all the deployed security countermeasures and the layout costs that represent the travel cost of construction resources on site and the cost of relocating temporary facilities. The performance of the developed framework was analyzed using an application example that demonstrated its capabilities in planning construction site security systems and generating optimal tradeoffs between minimizing security risks and minimizing overall site costs.

CHAPTER 8
SUMMARY

8.1 Summary

The present research study focused on the optimization of site layout and material logistics planning during the construction of critical infrastructure projects. The new research developments of this study include: (1) new efficient models of dynamic site layout planning that overcome the limitations of existing models in generating global optimal solutions; (2) a novel material logistics planning model that considers existing interdependencies between material procurements and site storage decisions in the integration and simultaneous optimization of dynamic site layout and material procurement planning; (3) an innovative model for congested construction logistics planning that is capable of modeling and utilizing scarce interior and exterior spaces on construction sites in order to generate optimal construction logistics plans that provide optimal tradeoffs between minimizing total logistics costs and project schedule criticality; (4) a prototype automated multi-objective optimization system for construction logistics planning that is capable of seamless retrieval of project spatial and temporal data from available construction documents and generating optimal construction logistics plans; and (5) a new multi-objective optimization framework for the optimization of site layout and security systems of critical infrastructure projects.

First, two new optimization models are developed that are capable of generating global optimal solutions of dynamic site layout planning in order to minimize resources travel costs and facilities relocation costs while complying with various site geometric constraints. The first model, DSLP-GA, is implemented using Genetic Algorithms while the second model, DSLP-ADP, is formulated using Approximate Dynamic Programming. These two models are designed to optimize facilities locations and orientations over a number of construction stages to minimize total layout costs, which include the travel cost of construction resources moving between site facilities and the cost of relocating temporary facilities between construction stages. Furthermore, the developed models consider four types of geometric constraints (boundary, overlap, distance, and zone constraints), which can be used to represent site space availability as well as any imposed construction operational and/or safety requirements. The performance of these two models is evaluated using two examples. The first example illustrates the efficiency of the developed models and their ability to outperform existing models in generating global optimal solutions. In the second example, the DSLP-ADP model showed outstanding performance in both efficiency and effectiveness, compared to the DSLP-GA model, for different problem sizes and complexities. On the other hand, the DSLP-GA model presents a set of unique advantages over the DSLP-ADP model including its multi-objective optimization capabilities and its simple modeling approach.

Second, a novel model of construction logistics planning (CLP) was developed to enable the integration and simultaneous optimization of critical planning decisions of material procurement and material storage layout on construction sites. Procurement decision variables are designed to identify the fixed-ordering-periods of each material in every construction stage, while dynamic layout decision variables are designed to identify the locations and orientations of material storage areas and other temporary facilities in each construction stage. The model utilizes Genetic Algorithms to generate optimal material procurement and layout decisions in order to minimize four types of construction logistics costs, including: material ordering, financing, stock-out, and layout costs. The performance of the developed CLP model is evaluated using an application example, which illustrated the model capabilities in: (1) generating optimal procurement decisions that minimize ordering, financing, and stock-out costs while considering site space availability; and (2) generating optimal layout decisions that minimize layout costs while complying with material storage space needs as well as operational and safety constraints.

Third, an innovative multi-objective optimization model for congested construction logistics planning (C2LP) is developed to help planners in utilizing interior building spaces and generating optimal logistics plans that minimize total logistics cost while minimizing the adverse impacts of interior material storage on project schedule. Interior building space is represented as a set of non-identical rooms that can be defined based on project architectural drawings, while exterior space is modeled as a grid of locations with planner-specified fixed spacing. The C2LP model utilizes multi-objective Genetic Algorithms to formulate and optimize four main categories of decision variables: (1) material procurement that includes fixed-ordering-periods of every material in each stage; (2) materials storage plan that includes material storage type, exterior grid location, exterior orientation angle, and interior storage priority of every material in each stage; (3) temporary facilities site layout that specifies exterior grid location and orientation angle for every temporary facility in each stage; and (4) scheduling of noncritical activities which specifies the number of maximum-shifting-days within their total floats. Interior material storage plans are generated using novel computational algorithms that consider four main types of interior storage constraints: rooms space capacities, rooms creation times, rooms partitioning times, and permissible material interior storage periods. Furthermore, new algorithms are developed to calculate material interior and exterior handling costs as well as shifting of noncritical activities. The

C2LP model utilizes Genetic Algorithms to generate optimal solutions that represent optimal tradeoffs between the two conflicting objectives of minimizing total logistics costs and project schedule criticality.

Fourth, a prototype automated multi-objective optimization system for construction logistics planning is implemented to support construction planners in generating optimal plans of material logistics and site layout. The system is developed in four main modules: (1) site spatial data retrieval module; (2) schedule data retrieval module; (3) relational database module; and (4) graphical user interface module. The site spatial data retrieval module facilitates the automated retrieval of site exterior dimensions and building geometric attributes (i.e., building footprint, floors, and rooms) from existing IFC-Based Building Information Models of the project. The schedule data retrieval module is designed to obtain the list of construction activities, their relationships, construction materials, and activities material demand from schedule database files that are exported from Microsoft Project. The relational database module is designed to store and integrate project spatial, temporal, and logistics input data considering their interdependencies in order to eliminate data inconsistencies. The user interface module is designed to facilitate data input and reporting of generated optimal material logistics plans.

Fifth, a multi-objective optimization framework is developed to enable construction planners of critical infrastructure projects to plan and optimize the implementation of site physical security systems and layout planning in order to minimize construction security risks and overall site costs. The framework is developed in four main phases: (1) risk identification and system modeling phase to identify security threats, attackers, and targets as well as site and security system geometric representation; (2) security lighting optimization phase to generate optimal tradeoff designs of fence and area lighting systems that consider the conflicting objectives of maximizing lighting performance while minimizing its system cost; (3) security-cost optimization phase to generate optimal site security systems that quantifies and simultaneously minimizes construction security risks and overall site cost; and (4) performance evaluation phase to test and analyze the performance of the proposed framework.

The aforementioned developments of this research study contribute to the current practices of site layout and material logistics planning and can lead to: (1) increasing the efficiency and global optimality of construction site layout planning; (2) improving construction productivity that can be realized due to the early coordination between material procurement and site space planning; (3) enhancing the utilization of interior building spaces for material storage areas while minimizing its possible negative impacts on construction operations; (4) increasing the security level on the construction sites of critical infrastructure projects; and (5) minimizing contractors site costs that cover resources travel time, material logistics, and site security systems.

8.2 Research Contributions

The main research contributions of this study can be summarized as follows:

1. Formulation of novel dynamic site layout planning models that outperform existing models in generating global optimal solutions while satisfying construction operational constraints by having look-ahead capabilities to consider the effects of first stage layout decisions on the layouts of subsequent stages.

2. Development of a novel construction logistics planning model that creates new knowledge on the integration and simultaneous optimization of the critical planning decisions of material procurement and site layout planning in order to minimize ordering, financing, stock-out, and site layout costs.
3. Formulation of an innovative congested construction logistics planning model that is capable of modeling and utilizing interior and exterior spaces in order to generate optimal logistics plans that provide optimal tradeoffs between minimizing construction logistics costs and minimizing the adverse impacts of interior material storage on project schedule criticality.
4. Implementation of a prototype multi-objective automated system for construction logistics planning that enables seamless acquisition and integration of project spatial, temporal, and logistics data as well as generating and reporting optimal material procurement and site layout optimal plans.
5. Development of a new multi-objective optimization framework for the optimization of site layout and security systems of critical infrastructure projects in order to minimize security risks as well as construction and security costs.

8.3 Future Research Work

Although the present study was able to fully achieve its research objectives, a number of additional research thrusts have been identified during the course of this study, including: (1) quantifying the effect of site layout and supply logistics planning decisions on construction productivity; (2) incorporating real time control and monitoring of construction logistics in order to continuously update and refine material procurement and site layout plans; and (3) optimizing construction production management.

8.3.1 Impact of Logistics Planning on Construction Productivity

Construction productivity is significantly affected by logistics planning decisions because of its critical dependency on material availability and site space organization. The present research study developed quantitative metrics to represent productivity-related impacts of material procurement and site layout planning decisions, such as stock-out, material handling, and resource travel costs. Nevertheless, there is still need for further research to investigate new metrics and algorithms that are capable of estimating the direct impacts of construction logistics planning decisions on the productivity of individual construction activities and on the progress of the whole project. For example, simulation models can be formulated to estimate the productivity of construction crews considering site layout decisions, which can be used to model the interaction of these crews on intersected travel routes and in congested construction spaces. Furthermore, regression models can be developed to estimate productivity losses and project delays due to late material deliveries and depleted material inventories onsite. These new metrics are envisioned to be integrated with the developed models of the current research study in order to consider the mutual impacts between construction productivity, material procurement, and site layout in the generation of optimal logistics plans.

8.3.2 Construction Logistics Monitoring and Control

Monitoring and controlling the performance of generated logistics plans is vital in detecting any variations in site conditions and updating previously generated plans. Construction sites are dynamic and changing environments that are difficult to predict during the planning phase. As a result, the planning input parameters and assumptions in this study can change over subsequent construction stages which affect the generated logistics plans. In addition, actual construction operations may not perfectly follow the generated logistics plans, such as procuring material from different suppliers or positioning site facilities in locations that are different from its layout plans. Accordingly, there is a need to conduct additional research to investigate the development of new logistics models that are capable of: (1) monitoring the implementation of construction supply and site logistics plans using innovative Information Technologies (IT) tools such as Radio Frequency Identification (RFID) system, computer vision, and image recognition; (2) storing and reporting the large sets of collected logistics monitoring data using efficient data management and mining techniques; (3) controlling construction logistics operations by analyzing the performance of implemented plans and generating a set of corrective actions and/or revising planning parameters; and (4) updating existing logistics plans to incorporate any corrective actions.

8.3.3 Optimization of Construction Production Management

Production management has been successfully utilized in the manufacturing industry by implementing operations research in optimizing and integrating material supply planning, production scheduling, and facilities layout in order to achieve customer satisfaction and cost effectiveness (Panneerselvam 2006). Similarly, the construction industry can greatly benefit of production management principles by developing novel planning and control models that integrate and simultaneously optimize three categories of critical decisions: (1) scheduling of construction activities in order to satisfy project completion, resources availability, and budget constraints; (2) material procurement to fulfill the demand of the construction activities in a timely and cost-effective approach; and (3) construction space planning that optimizes the allocation of site space to construction activities, temporary facilities, and material storage areas.

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Zhang, J.P., Liu, L.H., and Coble R.J. (2002). “Hybrid intelligence utilization for construction site layout.” Automation in Construction, Elsevier, 11 511 – 519.

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CURRICULUM VITAE

HISHAM M. SAID

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EDUCATION

Doctorate of Philosophy, Civil and Environmental Engineering,
University of Illinois at Urbana-Champaign, Illinois
Department of Civil and Environmental Engineering,
Major: Construction Management
August 2006 – May 2010 (anticipated)
Dissertation title: "*Optimizing Construction Logistics Planning of Critical Infrastructure Projects*"
Dissertation Advisor: Prof. Khaled El-Rayes
GPA = 4.0/4.0

Master of Science, Structural Engineering,
Cairo University, Giza, Egypt
Faculty of Engineering, Department of Structural Engineering
Major: Construction Engineering and Management
August 2003 – May 2006
Dissertation title: "*A Framework for Planning and Optimizing Bridge Deck Construction Using Computer Simulation*"
Dissertation Advisor: Prof. Mohamed Marzouk, Prof. Moheeb El-Said
GPA = 3.95/4.0

Bachelor of Science, Structural Engineering,
Cairo University, Giza, Egypt
Faculty of Engineering, Department of Structural Engineering
August 1998 – May 2003
GPA = 3.85/4.0, ranked 6^{th} out of 480.

PUBLICATIONS

It should be noted that "Zein El-Dien" was used in early publications and changed to "Said" to comply with USA immigration requirements.

Journal Papers

- El-Rayes, K., Said, H. (2009). "Dynamic Site Layout Planning using Approximate Dynamic Programming." Journal of Computing in Civil Engineering, ASCE, 23(2), 119 - 127.

- Said, H., Marzouk, M., and El-Said, M. (2009) "Application of Computer Simulation to Bridge Deck Construction: Case Study." Automation in Construction, Elsevier, 18(4), 377 - 385.
- Marzouk, M., Said, H., and El-Said, M. (2009) "A framework for multi-objective optimization of launching girder bridges." Construction Engineering and Management, ASCE, 135(8), 791 – 800.
- Said, H., El-Rayes, K. (2009). "Optimizing the Planning of Construction Site Security for Critical Infrastructure Systems." Automation in Construction, Elsevier. Accepted for publication.
- Said, H., El-Rayes, K. (2009). "Optimizing Material Procurement and Storage on Construction Sites." Construction Engineering and Management, ASCE, submitted and under review.
- Said, H., El-Rayes, K. (2009). "Automated System for Optimizing and Visualizing Construction Logistics Planning." In Preparation.
- Said, H., El-Rayes, K. (2009). "Optimizing Logistics Planning in Congested Construction Sites." In Preparation.
- Marzouk, M., Said, H., and El-Said, M. (2008). “Special Purpose Simulation Model for Balanced Cantilever Bridges.” Journal of Bridge Engineering, ASCE, 13(2), 122-131.
- Marzouk, M., Zein El-Dein, H., and El-Said, M. (2007). "Application of Computer Simulation to Construction of Incremental Launching Bridges." Journal of Civil Engineering and Management, Vilnius: Technika, Vol. 13, No. 1, pp. 27-36.
- Marzouk, M., Zein El-Dein, H., and El-Said, M. (2005). "Scheduling Cast-in-Situ on Falsework Bridges Using Computer Simulation." Scientific Bulletin, Faculty of Engineering, Ain Shams University, Vol. 41, No. 1, pp. 231-245..

Conference Papers

- **Said, H.**, and El-Rayes, K. (2010). "Optimizing Material Logistics Planning in Construction Projects." *Construction Research Congress*, Construction Institute (CI), American Society of Civil Engineers (ASCE), Banff, Alberta, Canada.
- El-Rayes, K., **Said, H.** (2009) "Global Optimization of Dynamic Site Layout Planning in Construction Projects." *Construction Research Council Congress (CRC) Conference, Construction Institute (CI), American Society of Civil Engineers (ASCE)*, Seattle, WA, USA.
- Marzouk, M., **Zein, H.**, and Elsaid, M. (2006) "Construction of Bridges using Cantilever Carriage Method: A Case Study." International Conference on Bridge Management Systems – Monitoring, Assessment and Rehabilitation, *Housing and Building National Research Center (HBRC)*, Cairo, Egypt.
- **Zein, H.**, Marzouk, M., and Elsaid, M. (2006) "On the Use of Ant Colony to Optimize Launch Girder Bridges." *International Conference on Bridge Management Systems – Monitoring, Assessment and Rehabilitation, Housing and Building National Research Center (HBRC)*, Cairo, Egypt.
- Marzouk, M., **Zein, H.**, Elsaid, M. (2006) "Bridge_Sim: Framework for Planning and Optimizing Bridge Deck Construction Using Computer Simulation." Proceedings of the 2006 Winter Simulation Conference, Monterey, CA, USA.

RESEARCH PROJECTS

- ***Optimizing Construction Logistics Planning for Critical Infrastructure Projects*** *(Fall 2006 – present), University of Illinois at Urbana-Champaign*. The objectives of this doctoral research project are to: 1) develop global optimization models of dynamic site layout planning; 2) develop a construction logistics planning and optimization model that integrates the decision of materials inventory and site layout planning; 3) formulate new metrics of evaluating the impact of site layout planning on the security level of critical infrastructure construction sites; and 4) develop a multi-objective optimization model that is capable of generating optimal tradeoffs between minimizing site security risks and minimizing site overall cost. This research was financially supported by NSF project number 0626066.
- ***Nighttime Construction: Evaluation of Lighting Glare for Highway Construction in Illinois*** *(Fall 2006 – January 2008), University of Illinois at Urbana-Champaign*. This $218,680 project was sponsored by the Illinois Department of Transportation (IDOT) to: 1) evaluate the impact of lighting parameters on glare; and 2) provide practical recommendations to reduce and control lighting glare in and around nighttime work zones.
- ***Planning and Optimization of Bridge Deck Construction*** *(Fall 2003 – Summer 2006)* Cairo University, Egypt. The objectives of this Master's research project is to: 1) investigate and study bridge deck construction methods known in the Egyptian construction industry; 2) develop special-purpose simulation models for each of the investigated construction methods; 3) develop a multi-objective optimization model to perform time-cost tradeoff optimization bridge deck construction using launching girder technique; and 4) develop a planning framework of bridge deck construction projects. This project won the 2008 award of distinguished post-graduate projects present by Center for Advancement of Post-Graduate Studies and Research in Engineering Sciences (CAPSCU).

RESEARCH PROPOSALS

- ***Optimizing the Measurement and Improvements of Roadway Lighting Performance in Qatar (2008)***. This proposal was submitted to Qatar National Research Fund (QNRF) to investigate the development of new models to assist transportation agencies in efficiently measuring highway lighting performance and optimizing the planning of highway lighting improvement projects (PI: Khaled El-Rayes).
- ***Evaluating The Compatibility, Durability And Visibility Of Pavement Markings On Portland Cement Concrete And Various Asphalt Surfaces (2009).*** This proposal was submitted to Illinois Center of Transportation (ICT) to evaluate pavement marking systems, in Illinois, placed on different Portland Cement Concrete (PCC) and various asphalt pavements to determine the pavement marking durability, compatibility and visibility (PI: Khaled El-Rayes and Co-PI: Liang Liu.).
- ***Clearview Font in Traffic Signs: Assessing IDOT Experiences and Needs (2009)***. This proposal was submitted to Illinois Center of Transportation (ICT) to determine the extent

of use of Clearview font in Illinois and issues involved with converting the exiting signs to Clearview font (PI: Khaled El-Rayes and Co-PI: Liang Liu.).

- ***Resource Allocation Framework to Meet Highway Asset Preservation Needs (2009)***. This proposal was submitted to the National Cooperative Highway Research Program (NCHRP) to develop and describe an analysis framework that may be used to allocate resources across principal categories of highway assets for which a DOT is responsible to ensure system preservation (PI: Khaled El-Rayes).

TEACHING EXPERIENCE

- **Teaching Assistant**, University of Illinois at Urbana-Champaign, Fall 2009. Assisted Prof. Khaled El-Rayes in teaching *CEE421 Construction Planning*:
  - Taught two lectures of the course that focused on construction scheduling techniques.
  - Collaborated in the preparation of course assignments.
  - Graded course assignments, projects, and papers.
  - Prepared and instructing lab tutorials of project planning software.
  - Leaded project discussion sessions to respond to students' questions and concerns.
  - Managed the course website to post course materials and announcements.

- **Certificate in Foundations of Teaching**, University of Illinois at Urbana-Champaign, May 2010 (expected). The Certificate in Foundations of Teaching is a program offered by the Center for Teaching Excellence (CTE) in UIUC to provide an opportunity for graduate students to explore teaching and to help them prepare for future responsibilities in an academic setting.

- **Graduate Teacher Certificate,** University of Illinois at Urbana-Champaign, May 2010 (expected). The Graduate Teacher Certificate is a program offered by the Center for Teaching Excellence (CTE) in UIUC that is designed to encourage TAs to develop their teaching skills and reflective practice. It provides opportunities to document teaching experience, professional development, and the constructive use of student feedback.

- **Teaching Assistant**, Cairo University, Faculty of Engineering, Department of Structural Engineering, August 2003 – August 2006. Worked as a teaching assistant in construction planning courses: 1) *STR404 Cost Estimation and Control*, 2) *STR480 Construction Engineering Senior Graduation Project*, 3) *STR208 Construction Planning and Control*, and 4) *CVE301 Engineering Economics*.
  - Collaborated in the preparation of course assignments.
  - Graded course assignments, projects, and papers of more than 200 students.
  - Prepared and presented tutorial sessions of project planning software.
  - Meet on a biweekly basis with students to supervise them in senior graduation projects.
  - Managed the Construction Management Lab (CML) by maintaining and updating project planning software on lab machines.

PROFESSIONAL EXPERIENCE

- **Contract Administrator**, Arab Consulting Engineers (ACE), Cairo, Egypt.
  01/2005 – 05/2005
  Project: City Stars Malls and Hotels, Heliopolis.
  Responsible for preparing bidding documents, searching for candidate bidders, evaluating bidders, initiation of contracts, and following up on the status of the contracts.
- **Junior Structural Designer**, COSMOSE Consultants, Cairo, Egypt.
  09/2003 – 09/2004
  Responsible for accomplishing steel and concrete design using either ECP or BSC and was involved in the following projects:
  - *Kuwait Villas*, Kuwait: Concrete design for different villas in Kuwait.
  - *San-Stifano Hotel*, Alex, Egypt: As a contractor consultant, office was responsible for the checking of design and drawing, and deciding on the construction method for the upper steel bridge floors between the two towers.
  - *Ali Saleh Mosque* – Yemen: As a contractor consultant, office was responsible for design and drawing checking, and design of false-work shuttering.
- **Structural Designer**, AAW Consultants, Cairo, Egypt. (Intern)
  Summer 2002
  Assisting in the design of concrete buildings, ground tanks, and elevated tanks, in different water reclamation plants in Egypt.
- **Site Engineer**, WEIR WESTGARTH Contractors, Muscat, Oman. (Intern)
  Summer 2001
  Assisting in site supervision in the construction of the 2nd phase of Al-Ghubra power station. Involved in the supervision of pile construction, pile testing, and generating construction monthly reports.

AWARDS AND HONORS

- **UIUC Teaching/Research Assistantship and Tuition Scholarship** (2006-2010). University of Illinois at Urbana-Champaign, IL, USA.
- **AAAEA Student Scholarship** (2008 and 2009). Awarded annually to distinguished Undergraduate or Graduate, Engineer, Architect, Computer Science student who is also a student member of AAAEA.
- **CAPSCU Prize for Distinguished Post-graduates** (2008). Awarded annually by the Center for Advancement of Post-Graduate Studies and Research in Engineering Sciences (CAPSCU) at the Faculty of Engineering, Cairo University to three distinguished post-graduate students. The decision is made on the basis of quality of research work and the publications produced by the thesis.
- **Cairo University Excellence Award** (2003). Presented by Cairo University to the most distinguishable students accumulatively over the 5-years Bachelor degree. Ranked first among 50 students of the structural engineering under-graduate program.

- **Students Union Excellence Award** (1999-2003). Presented by Students Union of Faculty of Engineering - Cairo University to the most distinguishable students based on their academic performance during the corresponding year.

PROFESSIONAL SERVICE

- **Reviewer**, Journal of Construction Engineering and Management, ASCE (2007 - present).
- **Reviewer**, Journal of Computing in Civil Engineering, ASCE (2007 - present).
- **Member,** Career Services Council, University of Illinois at Urbana-Champaign (2009 – 2010)

PROFESSIONAL MEMBERSHIP

- **American Society of Civil Engineers (ASCE)**, Student member (2006 - present).
- **American Society for Engineering Education (ASEE),** Student Member (2009 – Present).
- **Phi Kappa Phi Honor Society**, Member (2009 – Present).
- **Arab American Association of Engineers and Architects (AAAEA)**, Student chapter in University of Illinois at Urbana-Champaign, Co-founder and Vice-president (2007 - present).
- **Egyptian Engineers Syndicate (EEC)**, Member (2003 – present)

LANGUAGE SKILLS

- **English**. Fluent speaking, reading, and writing knowledge.
- **Arabic**. Excellent speaking, reading, and writing knowledge.